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WORKSHOP ON RADIO SYSTEMS IN FORESTED  
AND/OR VEGETATED ENVIRONMENTS

J. R. Wait, et al

Army Communications Command  
Fort Huachuca, Arizona

February 1974

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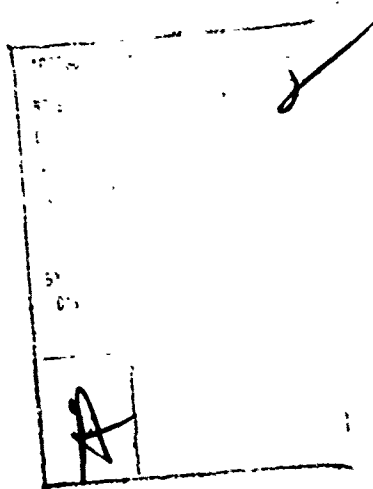
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<p>The purpose of the Workshop was to review the state-of-the-art in the theory of operation and design of radio systems for which the air/earth interface becomes a controlling factor. Each of the twenty technical papers are presented in summary, with the name of the author, his affiliation and address for each. The papers are principally devoted to radio and radar propagation in jungles and forests, path loss predictions, electrical characteristics of the forest and earth media, and lateral wave applications.</p> <p>The Working Group reports cover: 1) Application of Antenna and Propagation Theory; 2) Spectrum Usage Below 300 MHz (including UHF Radio 225-400 MHz, but exclusive of radar); 3) Spectrum Usage above 300 MHz (including radar above 30 MHz, but exclusive of UHF radio 225-400 MHz); and, 4) Environmental Descriptions (in relation to propagation and system performance modeling).</p> <p>Appendices provide names and addresses of all attendees, and a bibliographic summary of reports and articles from Project SEACORE, which was sponsored by the Advanced Research Projects Agency and the U. S. Army Electronics Command.</p>		

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WORKSHOP ON RADIO SYSTEMS IN FORESTED  
AND/OR VEGETATED ENVIRONMENTS

Edited by

J. R. Wait

R. H. Ott

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Office of Telecommunications  
U. S. Department of Commerce  
Boulder, Colorado

February 1974

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Advanced Concepts Office  
U. S. Army Communications Command  
Fort Huachuca, Arizona 85613

## FOREWORD

An important element of the mission of the Advanced Concepts Office of Headquarters, U. S. Army Communications Command, is to conduct studies whereby scientific knowledge can be utilized in the solution of current or foreseen problems affecting USACC's operational capabilities. The proceedings of this workshop review the state-of-the-art in the theory of operation and design of radio systems for which the air/earth interface becomes a controlling factor.

The proceedings were edited at the Institute for Telecommunication Sciences, Office of Telecommunications, U. S. Department of Commerce, Boulder, Colorado 80302, under Project Order ACC-409-73, by Dr's. J. R. Wait and R. H. Ott. Mrs. Thelma Telfer was responsible for arranging and, in some cases, retyping some of the manuscripts.

The organization, physical arrangements, contacting speakers and panel chairmen, inviting attendees, corresponding with all attendees, as well as other numerous administrative details, were all performed in a superb fashion by Mr. George C. Lane of USACEEIA and Mr. Eric R. Osborne of the Advanced Concepts Office, USACC.

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OPENING REMARKS  
WORKSHOP ON RADIO SYSTEMS  
IN FORESTED AND/OR VEGETATED ENVIRONMENTS

MG JOHN E. HOOVER  
DEPUTY COMMANDING GENERAL  
US ARMY COMMUNICATIONS COMMAND

Ladies and Gentlemen:

On behalf of the Commanding General of the Army Communications Command, MG Jack A. Albright, it is my pleasure to welcome you to this workshop. I hope you will find your stay with us both pleasant and worthwhile. We are indeed pleased that so many organizations have sent their engineers and scientists to this meeting to pool the store of knowledge in the topic area of Radio Systems in Forested Environments. This subject is of particular interest to the Army Communications Command, as we encounter it in planning, engineering and operating in many areas of the world in furtherance of our worldwide mission.

As many of you know, our first experience with conventional radio systems in the jungles of the South Pacific islands in WWII was less than favorable. Consequently, several energetic research programs were initiated to study the problems associated with radio wave propagation in a jungle environment.

By the early 60's, Dr. Wait, Dr. Tamir and Dr. Sachs, all of whom are with us today, presented theories concerning such propagation mechanisms. Almost simultaneously with the beginning of the SE Asia conflict, the Advanced Research Projects Agency of the Department of Defense undertook a large scale research project to study propagation in a tropical region. These studies were carried out over the next 10 years primarily in Thailand and here in the United States.

While these studies were in progress, the Army, including an element of ACOMM, the Navy and the Air Force, were experiencing radio communications difficulties in Vietnam. These problems are still fresh in our minds. Therefore, I think it is important to future planning, equipment design, and system configurations that the communications users and the research scientists compare notes at this time.

Six and a half years ago, Colonel Tom Doeppner, who is here today and who then was the program manager for the research studies in Thailand, called a meeting to discuss the technical developments to date and to decide what new efforts should be undertaken. To the extent possible, we have invited the participants in the 1967 meeting to be here today. We have also invited representatives of radio system users in the Army, Navy, and Air Force, to discuss their problems and past experiences.

Perhaps many of the users' problems can be solved by employing knowledge already gained by the R&D effort put forth so far.

A major goal of this workshop is to determine how the results of the R&D efforts to date can be translated into information and data useful to the engineers. Guidance and advice can then be made available to the users of radio systems to obtain optimum performance. Any gaps in present theory should also be identified now.

This week you will be discussing mechanisms, models, environmental structuring factors, etc.; but I hope you will do so in the light of such questions as "What prediction model is best for what situation"? "What engineering guidelines can be stated"? or "What design procedure should be considered"? Purposely, we have invited personnel experienced in the design and use of a wide variety of electromagnetic emitting devices. In so doing, we hope to keep the goals broad, yet to combine the knowledge and experience from many areas.

In addition to our peacetime missions, the Army Communications Command is assigned operational and maintenance responsibilities for Army communications systems in the theater of operations to the rear of the combat zone. In providing this theater Army communications system, we undoubtedly will be faced with the problems associated with radio systems in forested regions.

The theater communications systems must be flexible, reliable, and capable of heavy traffic loads. Currently and into the mid-range time frame, we expect to use multichannel line-of-sight and tropospheric scatter systems for command oriented and area network links. High-frequency radio systems may also be used, particularly when there are longer distances involved. In the long-range time frame, satellite systems will be operational for providing some of the intratheater links. However, our most recent indications are that the length of communication links within the theater Army communications systems may be stretched beyond that currently planned for. We may be faced with providing communications throughout an area 700 km wide by 600 to 1000 km deep. The distance between theater Army headquarters and the most distant corps headquarters may be 500 km or more. Until the satellite systems are fully operational, we must be prepared to provide communications within such an expanded area by using conventional systems.

During this workshop and the formulation of your final report, I hope you will consider the following additional points:

1. Frequency spectrum usage must be reduced as much as possible.
2. Vulnerability to electronics warfare must be minimized.
3. Communication equipment must be highly mobile and its power requirements minimal.

3

Your scope should be broad enough to encompass the interests of the Air Force, the Navy, and other Army agencies. The voices of the engineer and the user should both be heard. I hope the resulting summary report will provide the defense community with an authoritative statement as to the state-of-the-art as it applies to defense needs now and into the future.

Again, I welcome you and wish you a stimulating and profitable workshop.

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LUNCHEON REMARKS  
WORKSHOP ON RADIO SYSTEMS  
IN FORESTED AND/OR VEGETATED ENVIRONMENTS  
6 NOVEMBER 1973

LTG A. W. BETTS, USA, Ret.

"THE ROLE OF THE IN-HOUSE TEAM"

Gentlemen:

Since the selection of a subject for this talk was left up to me, I suppose I could be accused of preaching to the choir, but I assure you that that is not my intent. I know that this audience is well aware of what the in-house team is supposed to be doing. After all, everyone here has been pretty close to the process; nevertheless, the vantage point from which I have viewed in-house technical activities over the years is not necessarily the same as yours. In fact, it may be quite different.

Actually, if you sat where I did in the Pentagon, or where I now do in the Southwest Research Institute, you might just might, have a very different point of view than you now have. All of this is why I thought it would be useful to share some thoughts with you.

And just what do I see as the role of the in-house team? Briefly, as I saw it, when I was Chief, Research and Development, and as I see it now, the in-house team is in charge. This in-house team--the technical professionals, that is--is where the action is. If this team does its job well, development programs have a high probability of success. If this team does its job poorly, the probability is failure. It is that simple.

Of course, the technical team I am talking about doesn't go it alone. There are many others involved at all levels of government but that does not change what I just said.

I know there must be headquarters staffs to justify programs and defend the budget before Congress, and Congress has to approve the funding before anything significant can be done. And staffs have to apportion the funds and take other bureaucratic steps before the action levels can get things moving. And there are Project Managers and contractors; lots and lots of people get in the act. The Project Manager is the guy who picks up where the in-house technical team leaves off. He is the one whose performance depends so heavily on the quality of the preparatory work of the in-house team that leads into his project.

In spite of all those people, I still insist that the foci of technical competency, and the most important aspects of money control, reside with the technical professionals who create new concepts, who set the stage for program decisions.

Some of you are undoubtedly saying, "This guy never worked at the R&D action level," and you are correct, but I have been involved in supporting--or administering--R&D projects since 1945. I think I understand your problems. I think I understand the difference between legitimate cost growth and overruns born of incompetency.

The discouraging thing to me is that so many decisions are being made by bureaucrats who do not understand your problems, who think that every overrun or cost growth marks a bad program. They simply do not have the understanding to cope with justified changes in scope or technical approaches. Consequently, we continue to suffer from the image of careless overruns, an image that would have had an entirely different caste if the in-house team had not made a few very critical mistakes.

Let me illustrate with a few case histories, unfortunately not from communications projects. Of course, we could discuss MALLARD, but it might take all day.

Let's look briefly at the history of the M551, the airborne assault (AA/ARV) armored reconnaissance vehicle, the SHERIDAN. Some of you may remember, the conceptual requirement for this vehicle called for it to be the first armored vehicle to be designed as a system capable of firing both an anti-tank guided missile and a conventional round. You may also recall that Congressman Stratton, with the help of the GAO, had a political field day taking the Army to task for performance problems and consequent program slippage and cost overrun that the Army suffered with this armored system. Certainly, this system development did nothing for the Army's image.

Could the in-house team have prevented these difficulties? I say they could, and that is my reason for using it as a case study in this talk.

This weapon system called for three separate and distinct development programs, all of which were to push the state-of-the-art. The vehicle had to be light for airborne reasons, but it must also be armored and rugged. The guided missile was to be sophisticated, wire-guided, and it had to have high reliability to pay its way; and to add a complexity, the missile was to be launched from a gun tube that would also

fire a conventional anti-tank round. As if that wasn't enough, the anti-tank round was to have a heretofore unproved, combustible cartridge.

And we almost got away with it. All three developments went quite well until the emphasis shifted away from killing tanks in western Europe to delivering conventional support of infantry in Viet Nam.

That change in the operational need put the missile on the back burner and the combustible cartridge up front. It turned out that heat and humidity affected the burning rate of the combustible cartridge--hardly a very good prospect for use in the jungles of Viet Nam.

The problems were eventually solved, not by the Project Manager, but by the in-house team, but not until the damage to our reputation had been done. The key mistake, of course, was at the very beginning in going ahead with three full-scale development programs without having solved all the basic unknowns.

Another case history, the M60A1E2, a modification of the M60 main battle tank to give it a guided missile capability. The SHILLELAGH missile was working fine. The plan was simply to replace the turret of the in-production, reliable M60 A1 tank with a new turret with the same missile/cannon combination that had been successfully tested on the SHERIDAN.

The prototype tests revealed the usual problems that required correction before going into production, but the pressure was very heavy to accept these changes for application to the first production models as "well within the state-of-the-art and no problem." You have heard that before. In this case, the M60 production line was already running and the cost of shutting it down while we would have waited for further testing of the new turret would have been enormous.

As it happened, the cost of going ahead with production was very high in spite of the assurances that the corrections would be minor. We produced several hundred tanks and put them in storage! The key trouble was in the turret system controls; yet I remember reading the minutes of the IPR reporting on the prototype tests. The in-house team said that this was the best turret control system they had seen. That comment came from one source; others of the in-house professionals told us later that they knew the turret control system would give us severe problems--another mistake that could have been avoided if all the relevant information had reached the decision level.

The third example I'd like to discuss is the AH56 attack helicopter, the CHEYENNE, now defunct. This development program was one of those that began under the ground rules of Total Package Procurement. The contract was awarded on the basis of a paper design backed up by some test vehicle activity. The contractor was asked to commit himself to an incentivized, essentially fixed price development and he was required to quote production prices before he saw the first piece of hardware.

In spite of all that things went quite well until the contractor began to flight test the early development aircraft. You may recall that this aircraft had a hingeless rotor not like the conventional helicopters of that day. In the flight testing, a veteran test pilot was killed when the rotors developed a divergent instability. The blade flapping simply got so bad that it cut through the cockpit. The pilot never had a chance.

We learned then how little we knew about the dynamics of the control system that was being used with what was called the rigid rotor. That idea had been flown for many hours on a test vehicle, the XH51, with considerable success. In fact, it was that success that led us to see the rigid rotor as a low risk part of the development.

During the endless reviews we went through on the CHEYENNE, it finally surfaced that an Army test pilot who flew the XH51 had seen and reported the divergent instability that later destroyed a CHEYENNE prototype. At that time, the instability was corrected empirically and nothing further was done to try to understand it, or to report it to higher levels.

We eventually learned what caused it, and we were testing a new control system that cured the problem when the development program was killed. I firmly believe that that aircraft would have been a most effective weapon system worth every penny of its high cost. It could have been saved if the in-house team had but insisted on pursuing the work on the XH51 until they thoroughly understood every facet of the rigid rotor control system.

I believe those three development programs illustrate what I wanted to say about the role of the in-house team. That team buys for the government. They may buy research or development or production or baked beans. If these things are to be bought at a fair price, and with a fully satisfactory return to the government, the in-house team must know what they are buying--they absolutely must be technologically well informed.

That is where the action is!

## INTRODUCTORY NOTE

From

The Technical Program Chairman

An effort has been made to assemble a representative group of papers from authorities in the field of radio propagation in forested and jungle covered terrain. The main theme of the technical papers is the description and utilization of lateral wave phenomena in the context of point-to-point communication in such situations. Both the basic phenomenology and the operational experience are covered in varying degrees of depth.

The summaries of the papers here include both the contributions in the main technical sessions and the submissions from the working group sessions. The actual summaries from the working group chairmen are included at the end of this report. They have been coordinated by C. W. Bergman.

In my capacity as technical program chairman, I would like to thank all the speakers for agreeing to present their material and preparing summaries for this document. Also, I should like to thank Dr. R. H. Ott for acting as associate technical program chairman and Messrs. George Lane and Eric Osborne for helping with many administrative (and technical) problems that arose during the long period of hectic planning.

JAMES R. WAIT

CHAPTER I

PROGRAM REVIEW OF THE SOUTHEAST ASIA  
COMMUNICATIONS RESEARCH PROJECT

by

Robert A. Kulinyi

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Presented at

Workshop on Radio Systems  
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PROGRAM REVIEW OF THE SOUTHEAST ASIA  
COMMUNICATIONS RESEARCH PROJECT

by Robert A. Kulinyi  
Communications/ADP Laboratory  
US Army Electronics Command

I would like to start by giving my working definition of the title. This is not a program review in the formal sense that our DOD practice implies. Instead, I would like to set the stage, in a qualitative sense, for several papers which will follow, giving you, in effect, a review of quantitative aspects of this program.

You will find many references to the term SEACORE - it is an acronym for SouthEast Asia Communications Research. It was coined in 1962 primarily to cover activities under the Advanced Research Projects Agency (ARPA) Order 371 which, from an extremely modest beginning, expanded through some 21 amendments. This program was managed by the US Army Electronics Command (ECOM) at Fort Monmouth as Service Agent.

SEACORE followed two major lines of effort covered by contracts. The first was with the Jansky and Bailey (J&B) Division of Atlantic Research Corporation. This actually was pre-existing with respect to SEACORE, having started as an ECOM effort in early 1962 for a more modest program intended to accomplish limited path loss measurements in Panama. This work was redirected as an early amendment to ARPA Order 371 with greatly increased urgency. Site selection in Thailand began in the latter part of 1962. Eventually, J&B operated at several sites in Thailand, as shown in Figure 1. Another contract, in accordance with ARPA guidance, was with the Stanford Research Institute (SRI) for broader based tasks to be carried out both in Thailand and the US. SRI activities in-country are shown in Figure 2.

Now a few words to sketch in very briefly the achievements of the SEACORE Program. This is well demonstrated by a bibliography prepared by Mr. Morris Acker as part of our concluding SEACORE activities. It is attached as an appendix to this report. A quick scan of this bibliography shows 16 semi-annual and final report volumes from Jansky & Bailey. There were also in-house ECOM reports and others from contractual efforts with the Polytechnic Institute of Brooklyn.

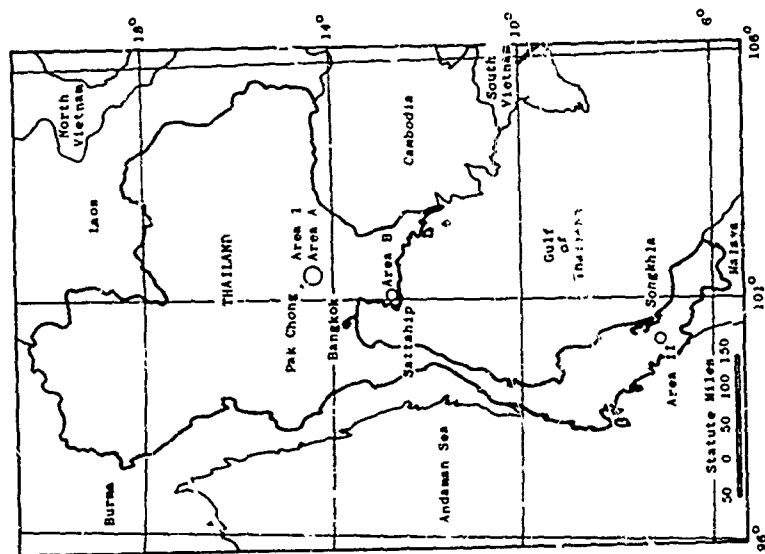


Figure 1 - Jansky & Bailey Test Sites

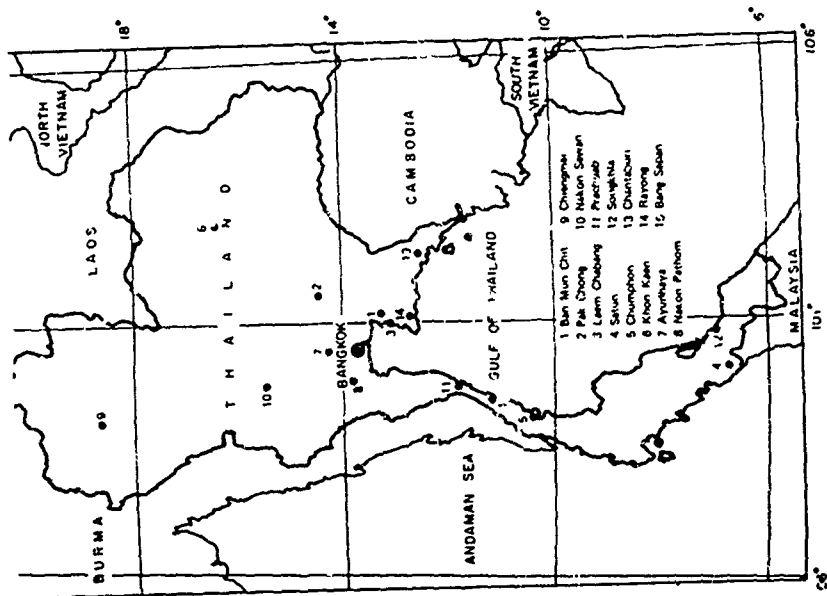


Figure 2 - SRI Test Sites

This is only a portion of material that has been generated in the technical literature as a result of SEACORE activities. The two major contractors and other people who have worked on the SEACORE Program have written presentations, papers and reports, many of which have found their way into public print. Recently, the Journal of Defense Research, published by ARPA, winter issue of 1972, contained an extensive article with the title Electromagnetic Propagation in a Tropical Environment authored by Doeppner, Hagn, and Sturgill, three veterans of SEACORE. This paper has some 46 pages of text and a bibliography of 100 items. A quick check shows that about two-thirds are from reports and other material generated in the SEACORE Program.

Our results were not confined to theoretical analyses or other types of software but at all times in the conduct of the program, there was ongoing activity concerned with hardware and operational matters. At least one significant item entered the inventory of the US Army as a direct result of the early work by ARPA in this Program. It is a high frequency manpack radio set, the AN/PRC-74, which was used in South Vietnam and elsewhere around the world.

It also seems appropriate to give an abbreviated chronology. Amendment No 1 to ARPA Order 371 was effective early in FY-63. Actually, work had begun earlier in the form of Army contracting with J & B and programmatic inputs to ARPA. The site survey and establishment of an ECOM field office, which was the first in country SEACORE presence, occurred in the second quarter of FY-63. This marked the start of a build-up phase which lasted until the latter half of FY-63. Some additional growth occurred from time to time as guidance shifted. Effort reached a peak in 1966 and 67.

Beyond that point the program began to go downhill until phase out in 1969. Closing of the ECOM Thailand field office occurred at the end of that year. Work under ARPA Order 371 and related work by ECOM phased out by 1972. Actually, the publication of material by SRI concluded only a few weeks ago with the issue of Special Technical Report 46, one of a series of late issues, due largely to the personal interest and leadership of George Hagn, who is active in this meeting.

The J & B work emphasized our interest in effects of the jungle on radio signals. Their major effort was to measure path loss in this environment and an attempt to relate these observations to distinctive characteristics of tropical terrain. Prime attention was focused on vegetation and two major types of forest were investigated at great length. First measurements

were made in a wet and dry evergreen forest. Other work was in a true rain forest, located only a few degrees from the equator in southern Thailand.

In Figure 1, the northernmost site (shown as Area I) was the wet and dry tropical forest. The closest inhabited place is the town of Pak Chong. The tropical rain forest was southernmost in Thailand and referred to as Area II. The nearest significant town is Satun. In some reports, it is also referred to as Songkhla. Path loss measurements were made over the electromagnetic spectrum from 100 kHz at selected frequencies to 10 GHz though not all frequencies were measured over each trail at all sites. Final processing of data by J&S was carried out in the Washington, DC area.

The work of SRI was much broader in nature covering specified operational analysis tasks defined by ARPA, a number of tests on communications equipment and three dimensional measurements of antenna characteristics in the jungle. As preparation for this effort, such antenna measurements were also made in the United States, both in open terrain and in temperate zone forests. From the start of the SRI effort, a significant part of their tasking was to involve qualified Thai engineers, military and civilian, in the work. This was accomplished as can be noted in various SEACORE related bibliographies which cite Thai engineers and scientists as authors and co-authors. Many basic measurement efforts in Thailand were undertaken by SRI: radio noise, ionospheric characteristics and geomagnetic observations.

A third major effort under SEACORE was provision of an electronics laboratory facility for use jointly by the US and Thais in Bangkok. This was one of the earliest hardware efforts in the SEACORE Program and is one of the more notable achievements. Within 9 months a laboratory was configured as a joint effort between Stanford Research Institute and the Electronic Defense Laboratory of Sylvania Electronics Systems as a contractor to ECOM. This included the physical construction and check-out in the US, transportation to, reassembly and energizing of the equipment in Thailand.

While not ranking high in terms of expenditure or overall scope, there were a number of efforts accomplished in-house at ECOM and other government agencies. Dr. Theodor Tamir, as an ECOM summer scholar, helped with our technical monitoring of SEACORE in 1966. This resulted in articles that dealt with lateral wave phenomena in jungle areas. Dr. David Dence of ECOM joined in studies with Dr. Tamir and extended some aspects

of the work. Significant help was received from Rome Air Development Center which provided their KC-135 aircraft and personnel to accomplish air-to-ground tests in conjunction with Jansky and Bailey in Thailand and this resulted in some significant SEACORE findings.

Figure 3 shows an air view of a landscape which is typical of southern Thailand. However, many areas to the North have as abrupt and variable features as you see here. A difficulty that we run into is to separate effects of underlying terrain from those of vegetation which, of course, has a set of variabilities all its own. In Figure 4 we see the northern test area, Pak Chong, the wet and dry type of tropical forest.

We actually built a small village in secondary growth jungle. It is approximately 15 miles from the nearest all-weather road and town. Test crews lived and worked in these buildings for a period of time. Then some men were rotated to Bangkok, assisting in the pre-processing of the data and recovering from jungle isolation.

In Figure 5, you see the southern site which was in a true tropical rain forest. The trees at Satun were much closer together. On the average, they were larger and taller than the trees encountered at Pak Chong. Rainfall was considerably greater and occurred without the interruption of a dry season.

In this case, the only residents were a group of service people that maintained the site and supported the technical working crew who were transported by air from the town of Songkhla on the east coast of the Kra peninsula. One of the difficulties that led to this arrangement is shown in Figure 6. This low ground-pressure vehicle was procured specially to assure that supplies and personnel could be moved to the site by ground transit under non-flying conditions. It is capable of a payload of 1 ton and traverses either water or most types of earth.

Vegetation was dominated by trees at this site. There are usually a few trees of great size. We also found, in the latter phases of our studies, these have a strong impact upon signals which are sensitive to multi-path effects. In Figure 7 we see a working area at the Satun site as well as some further details of the vegetation. The tower in this picture was used for studies at several frequencies above 400 MHz up to 10 GHz. It was used for height parameter studies by J & B.

In Figure 8 we see an instance of a mixed path case. This involves an open area, often with taller grass, at the edge

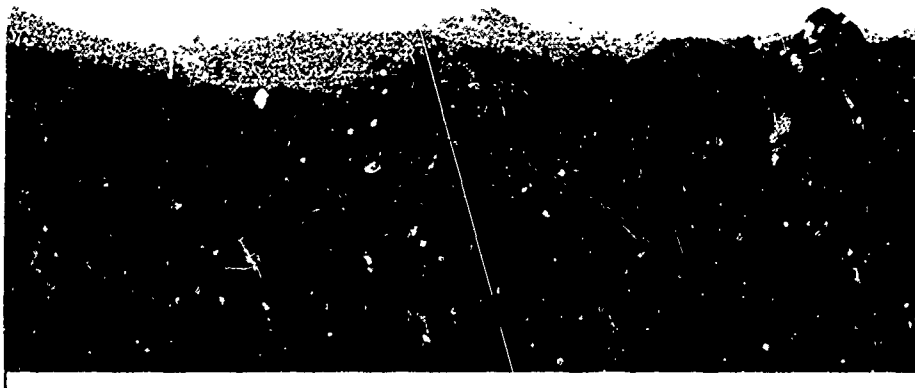


Figure 3 - Thailand Terrain from the Air

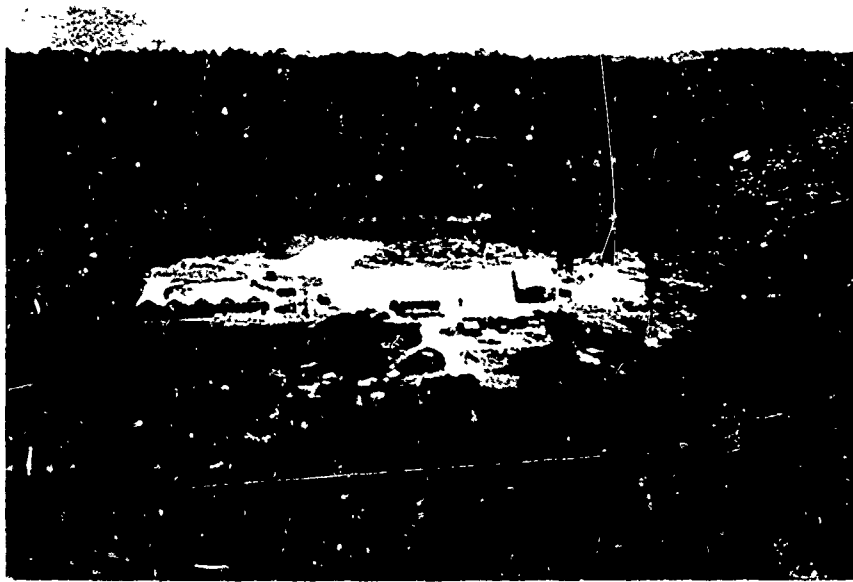


Figure 4 - Air View of Pak Chong Site

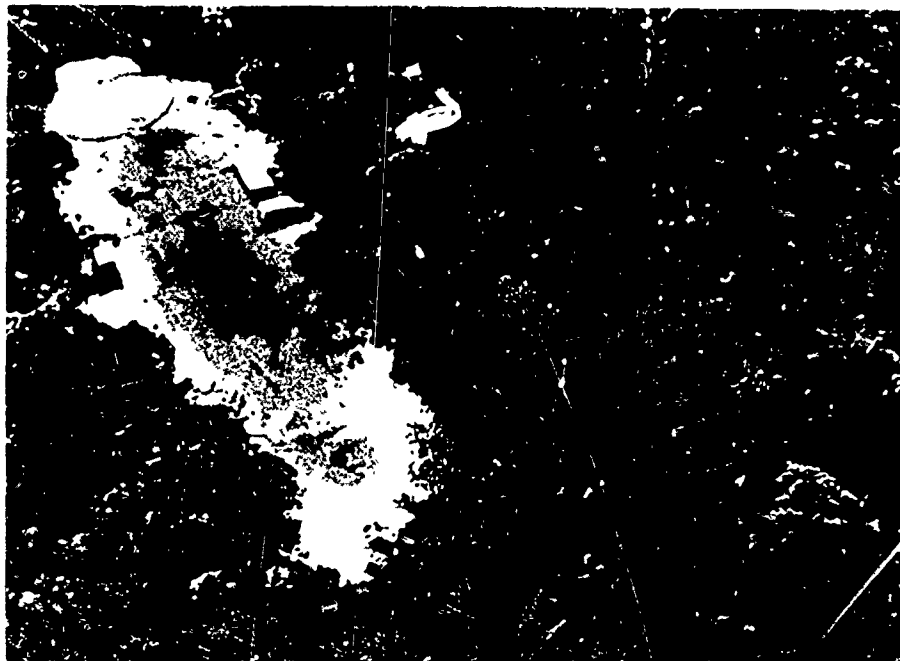


Figure 5 - Air View of Satun Site



Figure 6 - Special Vehicle on Trail Near Satun Site

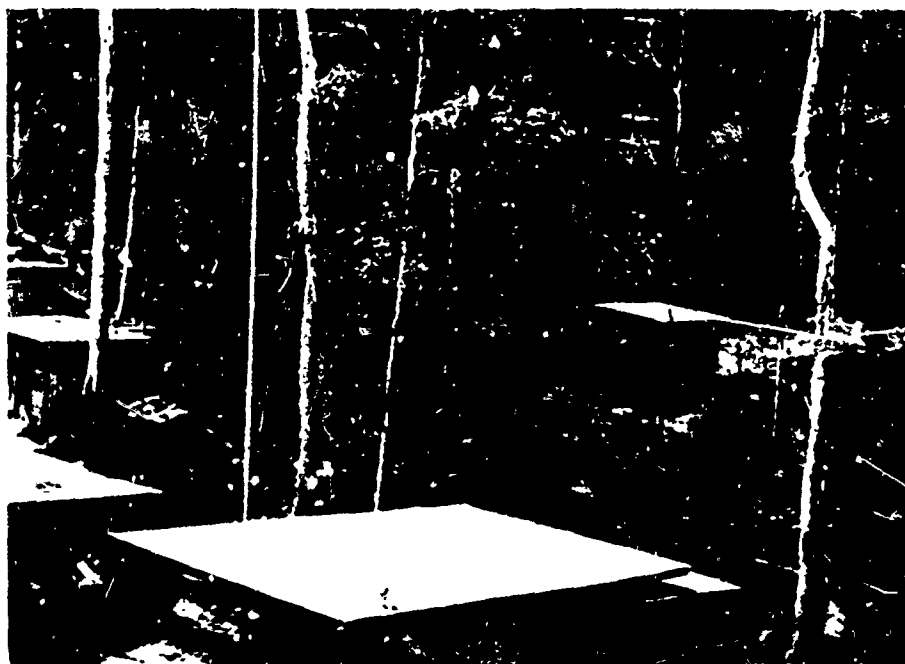


Figure 7 - Satun Site with Microwave Tower



Figure 8 - Chumporn Site with Special Transmitter

of the jungle. This was an SRI site near Chumporn which is a little over 100 miles north of Satun. The device on the man's back is a test radio transmitter with accurately calibrated power output. It will be received as the man walks across the interface and into the jungle. As he proceeds over various marked trails, effects of the jungle vegetation at a number of VHF frequencies are observed.

At this point, let me bring to your attention an event which, in a way, was the immediate predecessor of our workshop. I am referring to a 1967 Study Group Meeting sponsored jointly by ARPA and ESSA, which had for its objective a review and determination of the then-current status in the subject area "Environmental Effects on Short Range Communications". That is also the title of a meeting report which was published with DDC No. AD 660-040. The 1967 meeting really should have been called a workshop since, after receiving a number of technical presentations, it broke up into 4 working groups for specialized deliberations.

The findings of the 1967 study group were expressed in detail in a series of working group papers appended to the above report and in a series of recommendations. These were divided into four subject areas. (1). Exploration of the environment: subjects considered were problems of the upper atmosphere, surface and vegetative cover, terrain and radio noise; (2). Measurement techniques were concerned with: terrain irregularities, roughness, electrical parameters in vegetation and in the ground; (3). Systems and component studies addressed: evaluation of advanced systems, the relation of such concepts to current inventory items, antennas, near-field effects associated with antennas and related environmental parameters; (4). Model studies considered: simulation, mathematical and physical models where propagation was involved.

Space does not permit detailing results that flowed from that meeting. Pulse measurements were funded by ARPA and carried out by J&B in Thailand plus swept frequency observations which led to some very interesting computations of coherent bandwidth in the jungle channel. An effort of considerable interest was carried out at Brooklyn Polytechnic Institute by Dr. Tamir and his associates, jointly supported by ARPA and ECOM. This advanced our analytic capability relative to the lateral wave. It generated a very interesting example of physical modeling which served to verify and extend analytic findings on the lateral wave.

Now, lest we wax too complacent, it should be noted there are a few unsolved problems and work undone. One of these deals with gathering together information available from SEACORE into

a more coherent and accessible body of data, perhaps in the form of one or more text books. We need to provide a better mathematical modeling capability to include more aspects of the slab model. Our ability, specifically or statistically, to relate parameters of forested and vegetated areas, to current systems has not been sufficiently addressed. Furthermore, there has been a decline in experimental efforts which good scientific practice dictates should go hand in hand with analytic work that has been done in recent years. This has to occupy a high rank on our list of undone work.

Now to conclude my presentation, rather than trying to summarize further, I would like to illustrate briefly what can be done when the determination exists to get it done, even though one may be operating in an unfamiliar and exotic environment. In Figure 9 you see a view of the Electronics Laboratory, before it left the United States. This is probably the best overall view we ever had of what came to be called the T Lab. It is shown at a Sylvania Electronics Systems installation in Mountain View, California immediately prior to shipment. Each of the three major wings was thirty feet long and shipped as a unit completely stowed with electronic measurement gear and supplies. Also aboard was an excellent technical library.

In Figure 10 we see a view of the installation in a suburb of Bangkok. The significant thing here is the short period of time which separated conception of this facility, its construction and the throwing of the switch in Bangkok: about nine months overall. It functioned for the better part of 10 years as a part of the Military Research and Development Center activity in Thailand.

One of the distinctive features of the SEACORE program was effort on the part of all people involved to move ahead, improvise and solve problems as best they could on the spot. The last two figures give an example. In Figure 11 you see an early attempt to overcome some of the rainy season problems in the Pak Chong area. This was an attempt both to conduct a site survey and to do experimental work using a radio with a whip antenna. Naturally, this was found to be most inefficient, although presumably, there was a good ground connection.

In Figure 12 we see what might be called an "ultimate" solution, a mobile half wave dipole utilizing three elephants to maintain a much more efficient antenna capability along the trail. This concludes our SEACORE review. Papers to follow will provide more quantitative inputs on this and related subjects.

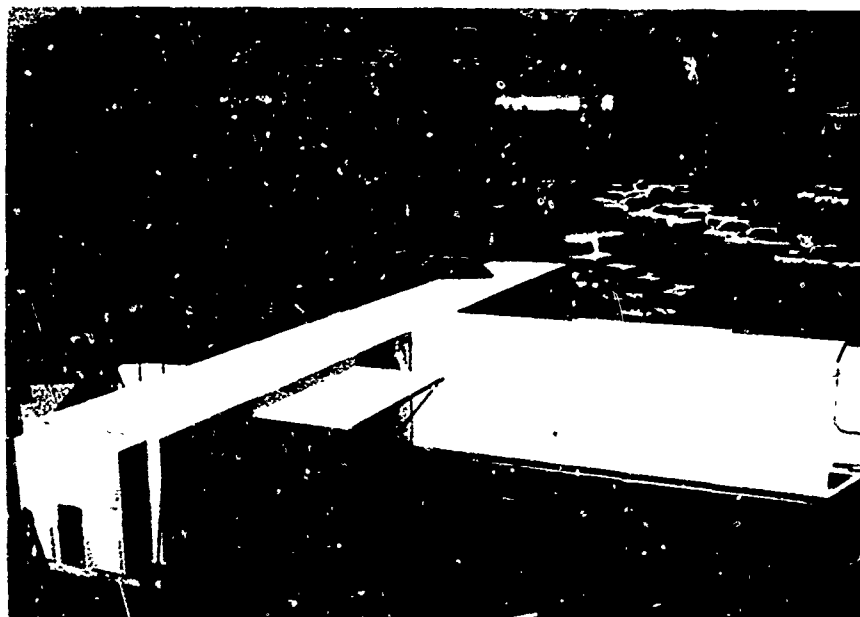


Figure 9 - T-Laboratory at Mt. View, California



Figure 10 - T-Laboratory in Bangkok



Figure 11 - Elephant with Radio and Whip Antenna

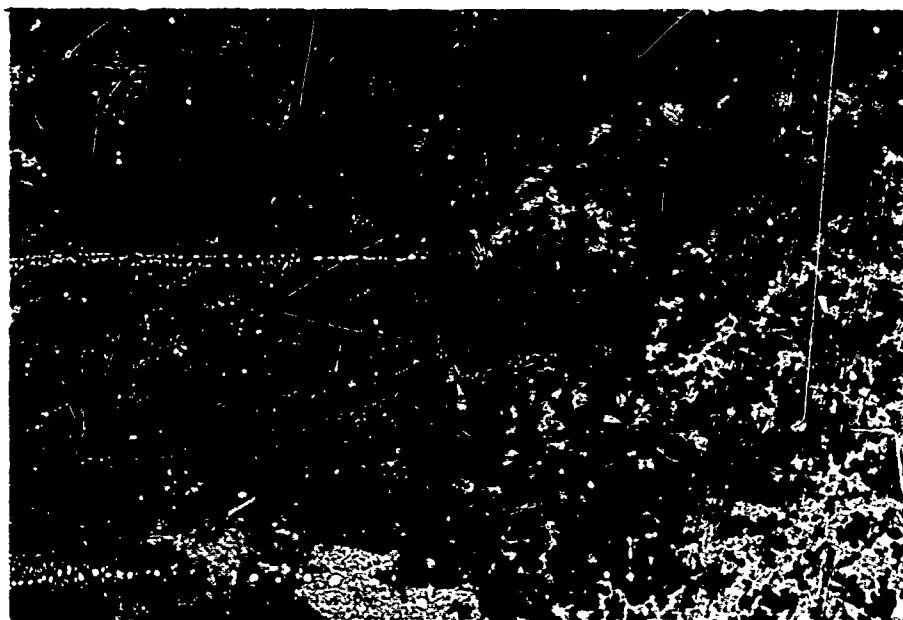


Figure 12 - Elephants on Trail with Mobile Half-Wave Dipole

LATERAL WAVE APPLICATIONS  
TO RADIO SYSTEMS

by

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Presented at

Workshop on Radio Systems  
in Forested and/or Vegetated Environments  
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## LATERAL WAVE APPLICATIONS TO RADIO SYSTEMS

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### I. Introduction

Preliminary studies /1-7/ of radio-wave propagation in a forest assumed that the signal travels along a line-of-sight path if both the transmitting and receiving antennas are inside the vegetation. Because the vegetation possesses a finite conductivity and thus behaves as a lossy medium, the field would then suffer a decay in the form  $\exp(-\alpha d)$ , where  $\alpha$  is the plane-wave attenuation factor and  $d$  is the distance traversed by the signal. Measurements of  $\alpha$  along relatively short distances  $d$  then indicated that losses would be prohibitively high and the use of a sky wave was suggested /4/ to avoid a long lossy path through vegetation.

Although the single line-of-sight path had been regarded as a reasonable model, some of the earlier investigators /1,6/ reported that the signal often appeared to arrive via a tree-top diffraction mechanism rather than directly through the vegetation. Such a mechanism has later been confirmed and systematically measured by the extensive field-strength measurements carried out under the SEACORE project /8,9/. Based on these measurements, theoretical studies have shown /10-13/ that the tree-top path is due to a lateral wave, which appears as a distinct field component if the forest behaves as a lossy layer. This layered geometry for a forest had been first suggested by Pounds and LaGrone /14/ and the evaluation of the electromagnetic field then reduces to the solution of a classical boundary-value problem involving a lossy dielectric slab. Although not specifically in the context of a forest layer, the lossy-slab problem was investigated in detail by Tamir and Felsen /15/ who showed that the lateral wave yields the principal field contribution for large distances  $d$ . Subsequent theoretical studies /9-13,16,17/, most of which were based on or were motivated by data provided by the SEACORE effort /8,9,18-20/, have indicated that the lossy-slab configuration and its attendant lateral wave represent a valid propagation model for the frequency range of 2-200 MHz. Below 2 MHz, the presence of a forest has only a negligible effect on radio waves; above 200 MHz, the scattering of the signal by the foliage produces local field variations which are usually so large that the lossy-slab model can have only a limited usefulness. Nevertheless, recent radar work at 435 and 1,300 MHz. has indicated /21,22/ that this modeling technique can be extended well above 200 MHz. provided that the statistical variation of the slab parameters is properly accounted for.

### II. The Lateral Wave Field

A complete description of radio-wave propagation in a slab model of a forest should include an ionospheric layer /12/, as shown in Fig. 1. The forest vegetation is then characterized by a relative complex permittivity

$$\epsilon_1 = \epsilon' (1 - j \tan \delta), \quad (1)$$

where measured data /18-20/ of  $\epsilon'$  range between 1.01 and 1.1, whereas  $\tan \delta$  varies between 0.01 and 0.15. The forest slab therefore behaves as a lossy dielectric, in contrast to the ground below which behaves as a lossy

conductor. Under these conditions and for large distances  $d \gg h$ , the signal radiated by a transmitter at T reaches a receiver at R via one of the following paths:

- (A) A direct line-of-sight wave as shown by the ray TR in Fig. 1, and reflected waves such as the broken ray TSR. Other reflected rays, which are due to reflection from the ground or to multiple reflections at the forest-air and forest-ground boundaries, are also present but they are omitted for clarity.
- (B) A sky wave, shown by the trajectory TJKLMNPQR, which is due to a single-hop reflection from the ionosphere.
- (C) A lateral wave along the path TABR, which travels mostly in the air region by skimming along the tree-top contour.

Because the direct and reflected waves under (A) above travel in the lossy medium, their amplitudes decay exponentially with  $d$  and therefore their contribution to the field at R is usually negligible. In contrast, the sky wave (B) and lateral wave (C) progress mostly in a lossless (air) region. However, as the sky wave may occur only within a narrow frequency range (about 3-10 MHz) and as its total trajectory is at least 100 km. long, it turns out [12] that the lateral wave accounts for the field at distances of practical importance (about 1-20 km.) in forest environments.

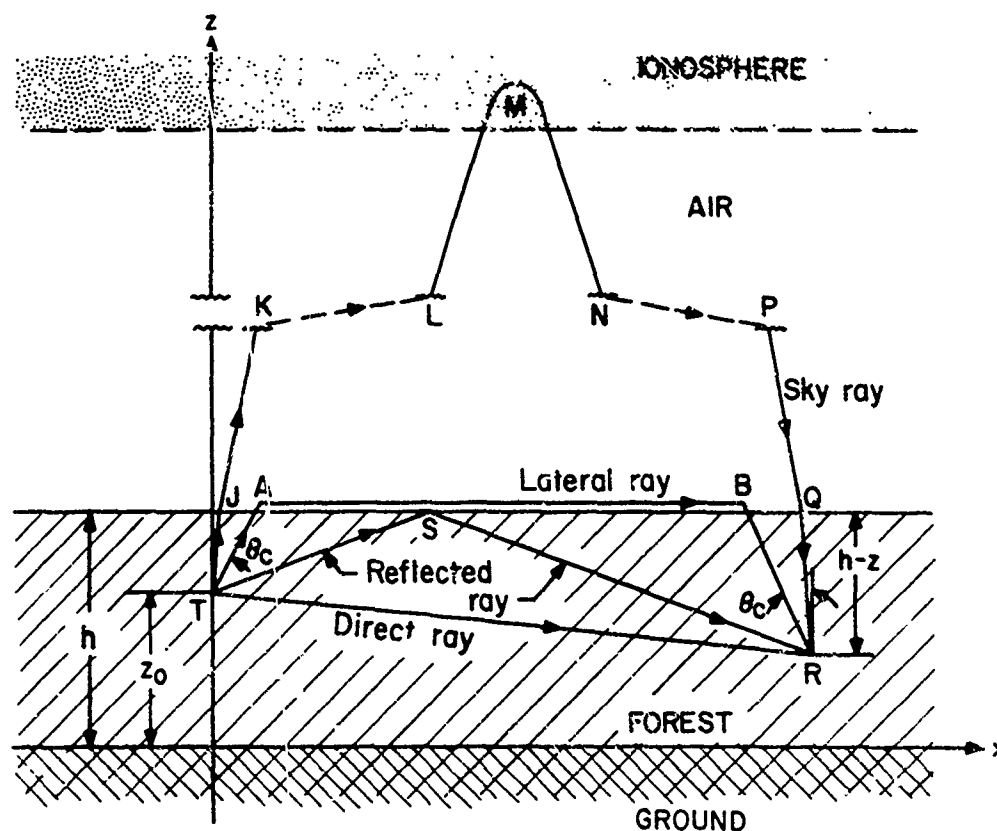


Fig. 1: Idealized planar geometry of a forest environment

The lateral wave is physically accounted for by a diffraction process, which differs from the geometric-optical character of either the direct and reflected rays in (A) or the sky wave in (B) above. If the forest layer is viewed macroscopically as a homogeneous (smoothed) slab, as was assumed in the theoretical studies /9-17/, the lateral wave is accounted for by the "ray" radiated at the critical angle  $\theta_c$  of total reflection, which is given by

$$\sin \theta_c = \frac{1}{\sqrt{\epsilon_1}} \quad (2)$$

The alternative microscopic view of the forest layer would have to consider the tree trunks, branches and leaves as individual scatterers /21/. At frequencies for which the scatterers' dimensions and refractions are small compared to wavelength, the fields due to randomly located scatterers appear to interfere constructively in a forward direction along the tree-top boundary, thus producing a resultant field that progresses along the trajectory AB. The lateral wave mechanism is therefore consistent with a forest layer whose composition is either homogeneous or discrete (with densely packed small scatterers), for frequencies up to about 200 Mhz. and possibly higher.

The lateral-wave field  $E_L$  at R due to a dipole at T is given /10-13/ by

$$E_L = \frac{60 I_a}{\epsilon_1 - 1} \cdot \frac{e^{-j k_0 [d + \sqrt{\epsilon_1 - 1} (2h - z - z_0)]}}{d^2} F(z) F(z_0), \quad (3)$$

where  $k_0 = 2\pi/\lambda$  is the plane-wave propagation factor in air,  $I_a$  denotes the dipole moment and  $E_L$  is measured in the xz plane wherein the transmitting dipole is located, the dipole being placed either horizontally or vertically. The functions  $F(z)$  and  $F(z_0)$  depend on the specific (horizontal or vertical) polarization being used, and on the ground and forest parameters.

As indicated by Eq. (3), the variation of the lateral wave is different from that of geometric-optical (line-of-sight, reflected and sky) waves. In particular  $E_L$  decreases with distances as  $d^{-2}$ , which should be contrasted to the smaller decrease  $d^{-1}$  of (spherical) geometrical waves. The implications of this and other characteristics of the lateral wave are discussed below.

### III. Radio Losses

For communication purposes, the radio losses incurred on the one-way propagation path between a transmitter at T and a receiver at R constitute a limiting factor in the design of radio systems. For both R and T being located in the forest, those losses have been examined by Dence and Tamir /16/ who showed that the total radio loss L (in db.) is given by the sum of four separate losses as follows:

1. An initial loss  $L_0$  which is obtained from Eq.(3) if the ground proximity is neglected, i.e.,  $F(z) = F(z_0) = 1$ , and if both T and R are located at the forest-air boundary, i.e.,  $z = z_0 = h$ , in which case  $L_0$  is proportional to  $|\epsilon_1 - 1| d^2$ .

2. A separation loss  $L_s$ , which is additional to  $L_0$  above if  $z$  and/or  $z_0$  are smaller than  $h$ . Thus  $L_s$  is given by the factor  $|\exp(jk_0 \sqrt{\epsilon_1 - 1} s)|$  of Eq. (3), with  $s = 2h - z - z_0$ .
3. An interference loss  $L_i$ , due to the proximity of the ground. This loss is inversely proportional to  $|F(z) F(z_0)|$  of Eq. (3); it turns out that  $L_i$  is particularly large if one (or both) antennas are close to the ground.
4. An antenna resistance loss  $L_r$ , which does not follow from Eq. (3), but is due to the fact that the input resistance of an antenna is strongly modified if the antenna is lowered close to the ground.

Because the last three losses  $L_s$ ,  $L_i$  and  $L_r$  generally increase if one (or both) antennas are lowered below the height  $h$ , it follows that a gain is achieved by raising one (or both) antennas. This antenna-height gain has been well documented by the SEACORE measurements /8,9,20/. It should also be noted that, although the foregoing considerations apply if both antennas are inside the forest, analogous results for the radio loss  $L$  can be derived if one of the two antennas is in the air region above the tree tops /17/. In this case, the signal arrives via the lateral wave only if the antenna in the air region is not too far above the tree tops. When this antenna is very high (say, more than a few wavelengths above the forest canopy), a refracted line-of-sight wave may account for a stronger signal than the lateral wave /17,23,24/.

In addition to the antenna-height gain, other observed effects can be explained by considering radio losses in conjunction with the formulas for the lateral wave. Thus, one finds that strong depolarization of the signal may occur /12/. At reasonable antenna heights above ground, the radio losses are generally smaller for horizontal polarization. However, vertical polarization may be preferable /16/ if one of the antennas must be very close to the ground.

#### IV. Radar Applications

Recent efforts /21-24/ have involved radar systems operating at frequencies above 100 MHz. for detecting targets (vehicles or personnel) located in a forest. Although the vegetation losses are known /8,9,20/ to be very large above 100 MHz., the operating frequency of these radar systems must remain high due to other factors such as range accuracy, available power, antenna gain, etc.

The principal effect of vegetation in radar detection is to produce a large amount of clutter. This unwanted clutter is especially strong in the case of ground-based systems because the return signal is then accompanied by very many echoes from a relatively large scattering volume, which severely limit the capability of the radar system. This limitation can be avoided in the case of moving targets by using Doppler techniques that suppress signal returns from stationary objects and/or from moving objects that have an average zero displacement, such as trees swaying in the wind. However, such a Doppler-radar system is still subject to propagation losses, which are larger in a forest than over bare ground. Hence the performance of the system is dictated by the propagation mechanism that holds under these conditions.

To illustrate these aspects, consider the radar equation for a mono-static radar system, which can be written as

$$\frac{P_{\text{rec}}}{P_{\text{tr}}} = \frac{\sigma \lambda^2}{4\pi} (\Omega)^2 \quad (4)$$

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where  $\sigma$  is the radar cross-section of the target,  $G$  is the antenna gain and  $D$  denotes the reduction in power due to propagation along a distance  $d$  between the antenna and the target. Thus, in free space this reduction is given by the spherical-front variation

$$D_s = \frac{1}{4\pi d^2} \quad (5)$$

However, if the radar antenna is in a forest, the field is given by the lateral wave  $E_L$  in Eq. (3), in which case, the proper value of  $D$  to be used in Eq. (4) becomes

$$D = \left| \frac{\lambda}{\pi(\epsilon_1 - 1)d} \cdot e^{-j k_0 \sqrt{\epsilon_1 - 1} (2h - z - z_0)} F(z) F(z_0) \right|^2 D_s \quad (6)$$

Because of the factor  $\lambda/d$  in Eq. (6), the ratio  $P_{rec}/P_{tr}$  varies as  $d^{-8}$  rather than as the free-space variation  $d^{-4}$ . In addition, the other factors inside the magnitude signs of Eq. (6) yield a value for  $D$  which is generally smaller than  $D_s$ . One may then define a terrain factor

$$L_{t2} = 20 \log (D_s/D), \quad (7)$$

where the subscript 2 in  $L_{t2}$  denotes that the result refers to a two-way terrain loss.

The terrain factor  $L_{t2}$  represents a figure of merit, which determines the (usually decreased) capability of a radar system in any given specific environment as compared to its operation in free space. In addition to  $L_{t2}$ , other deterioration in the radar performance may be due to the fact that the radar cross-section  $\sigma$  and the antenna gain  $G$  of Eq. (4) may, under actual terrain conditions, be substantially different from those in free space. However, it is believed /23,24/ that the influence of  $L_{t2}$  is greater than that of other possible factors.

Analogous considerations hold if the antenna is located above the tree tops, in which case Eq. (3) is replaced by another expression /23/. For the frequency range of 100-1000 MHz, it was found /24/ that, for a given antenna aperture, the deterioration in the performance of a Doppler radar system due to the presence of a forest is less severe at lower operating frequencies. However, this result holds only if the terrain factor  $L_{t2}$  is considered; of course, other factors may affect the choice of an optimum frequency for such a radar system.

## V. Concluding Remarks

Because the large amount of data now available shows a strong degree of correlation with the theoretical results obtained from a lossy-slab model, it appears that this model is quite adequate in predicting average propagation conditions in forest environments. In particular, if the antennas are inside or close to the vegetation layer, the propagation mechanism is in the form of a lateral wave.

The forest slab model is instrumental in providing predictions for radio losses and other propagation conditions, but the accuracy of these predictions depends on a precise knowledge of the complex permittivity  $\epsilon_1$  of the forest. To improve propagation predictions in the future, further measurements of  $\epsilon_1$  should be undertaken; such measurements should also be carried out in forest environments that are different

from the specific tropical jungles covered under the SEACORE project /18-20/. In the context of further studies, it should also be noted that a few mixed-path conditions have been considered /9-11,17,21-24/, but more extensive and systematic investigations into paths that traverse only partly through a forest need to be carried out to achieve a clearer understanding of the effects of vegetation on radio waves.

From another point of view, it is worthwhile to emphasize that the lossy-slab model has been shown to be adequate in providing results for the field average (or mean value), but no satisfactory models are as yet available for obtaining the field variance. Even those models that assumed random variations of the lossy slab parameters /21,22/ had to be restricted to small variations of unknown magnitude. Both experimental and theoretical studies into the statistical nature of a forest environment are therefore required to formulate design criteria for the efficient operation of future radio-wave systems.

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ELECTRICAL PROPERTIES OF FORESTED MEDIA

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in Forested and/or Vegetated Environments  
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## ELECTRICAL PROPERTIES OF FORESTED MEDIA

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### 1. Introduction

This paper discusses the electrical properties of vegetation and forests. The characteristics of a single tree are discussed, and then a group of trees is considered from both a microscopic and a macroscopic point of view. Methods for calculating and measuring the macroscopic electrical properties of a forest are discussed, and example results are presented. Problems in the determination of the electrical properties of forests and vegetation are discussed.

### 2. Electrical Characteristics of a Single Tree

A single oak tree was successfully modeled by Arnold, et al.<sup>1</sup> as a conducting sphere mounted on a grounded conducting mast for predicting the effect of a living tree on the earth's fair weather electrostatic field near the tree. At HF, the radar cross-section of an oak tree was measured by Steele.<sup>2</sup> He concluded that the vertical trunk made the main contribution to the scatter. Steele<sup>3</sup> applied his results to the calculation of HF backscatter from terrain. The patterns of VHF radio waves scattered from an isolated tree have been studied by Lorchirachoonkul;<sup>4</sup> he also studied the driving-point impedance of a dipole near a tree trunk. The radar clutter spectrum of a single tree was studied at UHF by Huerta, et al.,<sup>5</sup> who predicted a Doppler spectrum useful in radar application. Trees were considered for use as antennas by Squire.<sup>6,7</sup> Trees were investigated more recently for use as electrically-driven antennas by Dickinson, et al.,<sup>8</sup> Hagn and Parker (see discussion on p. 2 of Ref. 4), and Lorchirachoonkul<sup>4</sup> -- all with relatively discouraging results. Ikrath, et al.<sup>9,10</sup> used a helical toroid to excite a single tree located in a group of trees as a method of coupling energy into a forest -- with encouraging results. Taylor, et al.<sup>11</sup> studied the effect of a single tree upon a nearby open-wire transmission line and concluded that it loaded such a line as a lossy capacitor.

Plants, like people, are composed mostly of water, and the similarity of the response of plant and human tissue to electrical stimulus has been noted by Lawrence.<sup>12</sup> Ikrath, et al.<sup>9</sup> commented on the increase of a plant's internal resistance when subjected to electrical trauma. Pickard is currently studying the electrical response of plants to trauma.<sup>13</sup> The bio-electric potentials of plants and their functional significance have been studied by Fensom,<sup>14,15</sup> and Baxter<sup>16</sup> has even observed the electrical response of plants with a polygraph! The topics in this paragraph are mentioned only in passing. Some of them may be germane to the study of trees as antennas, but the author is not able to assess their accuracy or potential utility for this application.

Dickinson, et al.<sup>8</sup> estimated the intrinsic conductivity of a eucalyptus tree trunk to be 0.24 mho/m at HF. This was significantly higher than the VHF estimates of Parker and Hagn<sup>17</sup> for willow leaves and branches (0.03 mho/m) and the range of values inferred by Parker and Makarabhiromya<sup>18</sup> for cut tropical vegetation (0.025-0.06 mho/m). Hagn and Barker<sup>19</sup> concluded that the intrinsic conductivity of vegetation at HF and VHF probably was in the range 0.01 to 1.0 mho/m.

These characteristics of single trees are interesting in their own right, but it is also important to consider the electrical properties of a large enough group of trees to consider modeling the forest as a continuous slab as suggested by Pounds and La Grone.<sup>20</sup>

### 3. The Slab Model of a Forest

We know that a forest is electrically inhomogeneous and anisotropic, and that it is physically discontinuous and has an irregular air-vegetation interface. But we accept (as the simplest approximation) for modeling purposes a continuous medium of constant height that is homogeneous and isotropic. As a minimum electrical and physical description, we need to determine the effective macroscopic electrical properties of such a slab (e.g., the effective complex dielectric constants of the ground and vegetation) as well as its effective height. There are two basic approaches to determining the effective macroscopic complex dielectric constant of a group of trees: microscopic and macroscopic.

#### 3.1 Microscopic Approach

The microscopic approach consists of solving the detailed problem of the current density flowing in each individual tree illuminated by an incident wave for a given geometry, summing the resulting re-radiated waves with the correct amplitudes and phases to give the resultant field vector at a given point, and relating the result back to the effective electrical properties. This is essentially a deterministic scattering approach,\* and theoretically one could use knowledge of the scatter from a single tree (or its equivalent conducting cylinder as discussed by Steele<sup>2</sup> and by Lorchirachoonkul)<sup>4</sup> and the principle of super-position to obtain the desired result. There are many potential benefits if the problem could be solved in this manner. For example, the statistics of the fluctuations of radio system loss could be derived by successive computations of the resultant field for different receiver locations for a given tree height and spacing geometry chosen from the appropriate joint distribution. Also, channel distortion effects (e.g., multipath) could be deduced from such a detailed model. As mentioned above, such an approach would, if properly done, yield the macroscopic properties (effective complex dielectric constant) of the forest considered to be a lossy dielectric slab. But the

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\*The scattering problem has been treated theoretically by Vance and Spence<sup>21</sup> using a 2-point correlation of the refractive index of the forest — considered to be a random medium.

problem is most difficult in that extremely good models for a single tree would be required (e.g., perhaps at HF and certainly at higher frequencies it would be necessary to include the effects of branches as well as the trunk), and much computer capacity would be needed. Hence, this approach is not practical at the present time. To date, the only successful generalization from modeling a single tree to modeling a group of trees known to the author has been the model for Doppler developed by Huerta, et al.,<sup>5</sup> although the transmission-line approach outlined in Chapter VI of Taylor, et al.,<sup>11</sup> may work for the effective macroscopic electrical properties. As a result of the complexity of the microscopic approach, most of the efforts to date have gone into using a macroscopic approach to determining the complex dielectric constant used in the half-space<sup>22</sup> or slab models<sup>23-26</sup> to compute mean (or median) basic transmission loss and antenna characteristics.

### 3.2 Macroscopic Approach

The classical approach involves finding the polarization vector,  $\bar{P}$  for a given volume (equivalent dipole moment per unit volume) for a given applied electric field vector  $\bar{E}$ :

$$\bar{P} = p\bar{E}, \quad (1)$$

where  $p$  is a scalar quantity called the polarizability of the medium. The electric flux density vector,  $\bar{D}$ , (which is independent of the properties of the medium) is related to the electric field vector  $\bar{E}$ :

$$\bar{D} = \epsilon_0 \bar{E} + \bar{P} = \epsilon_0 \bar{E} + p\bar{E} = \epsilon_r \epsilon_0 \bar{E}. \quad (2)$$

where  $\epsilon_0$  = permittivity of free space.

$\epsilon_r$  = effective complex relative dielectric constant of the medium.

The polarizability is deduced from a set of equations called the constitutive relations for the "equivalent continuous medium," which is our model for the actual medium consisting of air, trees, underbrush, etc. The refractive index for the medium ( $n$ , the ratio of the phase velocity of a wave in the medium to the speed of light in vacuum) can be computed:

$$n = (1 + p/\epsilon_0)^{1/2} = (\epsilon_r)^{1/2} = (\epsilon_r' - j60\sigma\lambda)^{1/2} \quad (3)$$

$$\text{or } p = \epsilon_0 (\epsilon_r - 1) = \epsilon_0 (n^2 - 1)$$

where  $\epsilon_r'$  = real part of effective relative dielectric constant.

$\sigma$  = effective conductivity of the forest in mho/m.

$\lambda$  = free-space wavelength, in meters.

But how can we determine the polarizability of a forest (i.e., how can the values for  $\epsilon_r$  be obtained)?

### 4. Theoretical Calculations of the Macroscopic Forest Parameters

One approach to estimating  $\epsilon_r$  of the slab is to assume that a certain fraction of the slab volume is occupied by vegetation (mostly water, with  $\epsilon_r' \approx 80$ , and a little cellulose, with  $\epsilon_r' \approx 5$ ) and

that the remaining fraction is air ( $\epsilon_r' = 1$ ). We can then compute the dielectric constant of the mixture. If it is assumed that the dielectrics are arranged in parallel layers we can compute an upper bound, and if we assume the dielectrics are arranged as slabs in series we can compute a lower bound. This approach has been used by Lippmann<sup>27</sup> and by Parker and Hagn<sup>17</sup> but the bounds obtained are too large to be useful for radio propagation problems. The same general approach can be used for bounding the effective conductivity of the slab but it is difficult to estimate accurately the intrinsic conductivity of the vegetation. To attempt to narrow the bounds on  $\epsilon_r$  it is necessary to consider the actual spatial distribution of the vegetation. Pounds and La Grone computed  $\epsilon_r$  for a pine forest by calculating the polarizability of the medium containing pine needles. They used the theory developed for artificial dielectrics made from conductors. Even then they were forced to employ some rather gross assumptions to compute  $\epsilon_r'$ , and they required measured propagation data to make a rough estimate of  $\sigma$ . It is concluded that  $\epsilon_r'$  can be calculated for some simple special cases but that measurements are needed for determining  $\epsilon_r$  for living vegetation.

## 5. Techniques for Measurement of the Macroscopic Forest Electrical Parameters

Numerous techniques for measurement of  $\epsilon_r$  for a forest have been studied, as described below.

### 5.1 Inference from Comparisons of Propagation Measurements and Analytical Model Predictions

The most direct approach to estimating slab electrical parameters for use in propagation models for basic transmission loss (or equivalent) is to fit an analytical model containing  $\epsilon_r$  to measured propagation data by adjusting forest height and  $\epsilon_r$  for the forest and the ground. This method has the advantage of yielding the empirically derived values that are directly useful in the model of interest, but it has the disadvantage that the parameters are not uniquely determined. It is possible to use height-gain measurements in the forest near the air-forest interface to measure the lateral wave attenuation constant,  $\alpha_L$ <sup>22</sup>—when the transmitter-receiver separation is sufficient so that the lateral wave is the dominant propagation mode. Note that  $\alpha_L$  contains information about  $\epsilon_r'$  and  $\sigma$  (one equation and two unknowns). Hence, it is necessary to make another measurement and solve another equation containing  $\epsilon_r'$  and  $\sigma$  (e.g., measure basic transmission loss at very close range and fit the numerical solution developed by Wyatt).<sup>24</sup>

Thus far we have talked about solving for  $\epsilon_r$  for a homogeneous, isotropic slab. This approach has been successful when applied to predicting the gross features of basic transmission loss for  $f < 300$  MHz, but it is known that the forest is anisotropic at VHF and below. Data from various sources indicate that  $\epsilon_r'$  can be considered isotropic but that the forest conductivity is greater for vertical polarization for  $f < 300$  MHz. This is not surprising because of the predominant vertical component of most vegetation

and because of the size (in wavelengths) of the horizontal tree branches. A further complication is that actual forests are often not homogeneous with height or distance. These cases can be included in the model,<sup>28</sup> but with rapidly increasing complexity--at least as far as inferring the required  $\epsilon_r$  values.

#### 5.2. Antenna Pattern Techniques

Another method of estimating forests electrical properties is to use a model for the directivity pattern of an antenna located in a forest and compare computed directivity patterns with measurements. This technique has been employed by Barker, et al,<sup>29</sup> at HF and VHF, and by Muehe and Cartledge<sup>30</sup> at UHF. It is useful for estimating  $\epsilon_r$  and for  $f < 1\text{GHz}$ , but is increasingly hard to use for  $f > 500\text{ MHz}$ .

#### 5.3. Wave-Impedance Technique

The measurement of E and H fields as a function of frequency in air and in vegetation--as proposed by Reeve and Adams<sup>31</sup> appears to be a promising method of estimating  $\epsilon_r$  and  $\sigma$  of a forest in the frequency range where  $\sigma \gg \omega \epsilon_r$  ( $\omega$  = radian wave frequency). For most forests, this frequency range will begin near the lower end of the HF band or below.

#### 5.4. Open-Wire Transmission Line Techniques

Measurements of the driving-point impedance of open-wire transmission line (OWL) probes inserted into the vegetation can be used to estimate  $\epsilon_r$  for the volume in proximity.<sup>11,17,18,32</sup> Such probes give a direct estimate of average effective  $\epsilon_r$  when proper in situ sampling techniques are employed, and they also are useful for measuring vegetation moisture content.

#### 5.5. Parallel-Plate Capacitor Technique

The parallel-plate capacitor has been used with vegetation as a dielectric to estimate the electrical properties of vegetation,<sup>17</sup> but various physical difficulties (it is hard to place the capacitor in proximity of living vegetation) and electrical difficulties (e.g., radiation from the capacitor) made this method inferior to the OWL technique for in situ measurements.

#### 5.6. Cavity Technique

This method consists of placing cut vegetation into a cavity and observing the change in electrical characteristics (e.g., Q and resonant frequency) to estimate the electrical properties of the vegetation. This approach was considered by Parker and Hagn<sup>17</sup> and rejected for  $\epsilon_r$  measurements at HF and VHF, but it has been used successfully by McLeod and March<sup>32</sup> at 200 MHz for moisture content measurements.

### 5.7 Coaxial Transmission Line Technique

Broadhurst<sup>33</sup> has successfully used a coaxial transmission line to measure the intrinsic electrical properties of individual leaves and blossoms. This method does not appear promising for measurements of macroscopic slab parameters, but it is the only successful method used to date on fragile leaves and blossoms.

### 5.8 Reflection Coefficient Method

A standing wave pattern has been observed at distinct forest-clearing interfaces at VHF by Shrauger and Kreinberg<sup>34</sup> and at HF by Shrauger.<sup>35</sup> The peak and null locations relative to the interface and the null depths contain information about the forest electrical parameters. A fairly complex model might be required to use this method since the patterns become better defined as the frequency is decreased, and simple models become less applicable as the forest height in wavelengths decreases.

### 5.9 Remote Sensing Methods

The techniques described above involve either in situ or laboratory measurements. It is not always possible to have direct access to the vegetation of interest. It would be desirable to be able to use remote sensing techniques to estimate slab model input parameters ( $\epsilon_r$  and effective forest height). Work to date on remote sensing of vegetation (e.g., Refs. 36 and 37) has concentrated on crop identification, and multi-frequency/multi-polarization radar techniques have proven promising -- especially when supplemented by other remote sensing techniques (e.g., radiometry, multi-spectral photography, IR, etc.). Thus, it might be possible to identify the type of vegetation and its height using such techniques, and possibly information on vegetation moisture content. These data could be used to estimate  $\epsilon_r$  if such values had already been determined by one of the other techniques for the type of vegetation and the radio frequency of interest. A more direct approach is theoretically possible, since the electrical properties of the vegetation can influence the surface responses of both active (radar) and passive (radiometer) microwave sensors,<sup>38,39</sup> but the direct inference of forest electrical properties using synthetic aperture imaging radars, etc., has yet to be explored.

## 6. Estimates of Forest Macroscopic Electrical Properties

### 6.1 Effective Attenuation Constants

The two types of effective attenuation constants have been defined for use in studying propagation in forests: the attenuation through the forest considered as a slab,  $\alpha_s$ , and the lateral wave attenuation constant,  $\alpha_L$ .

#### 6.1.1 Forest "Through the Slab" Attenuation Constant, $\alpha_s$

Let us first consider the "through the slab" effective plane wave attenuation constant. La Grone<sup>40</sup> obtained data in

the band 0.1 to 1.2 GHz from numerous sources and calculated a least squares fit to get the frequency dependence:

$$\alpha_s = 1.3 \times 10^{-3} (f_{\text{MHz}})^{0.77}, \text{ in dB/m.}$$

It should be noted that the data he used exhibited considerable scatter around the fit. Hagn, et al,<sup>41</sup> obtained estimates of  $\alpha_s$  at VHF in an eucalyptus forest using the SRI airborne Xeledop.<sup>42</sup> The values obtained with vertical polarization were larger than the values obtained with horizontal polarization, and the difference between polarizations was greater at 50 MHz than at 100 MHz. Also, an increase in attenuation constant with frequency was observed for cross polarization that was not inconsistent with La Grone's  $(f_{\text{MHz}})^{0.77}$ , however, the values were approximately 2.5 times larger. Muehe and Cartledge,<sup>30</sup> using a more sophisticated propagation model to infer  $\alpha_s$ , obtained values in the range 0.1 to 0.3 dB/m at 400 MHz and 0.6 dB/m at 1300 MHz. The higher value at 400 MHz was obtained in more dense vegetation.

#### 6.1.2 Forest Lateral Wave Attenuation Constant, $\alpha_L$ <sup>22</sup>

The lateral wave attenuation constant  $\alpha_L$  is, for the same forest, much larger than  $\alpha_s$ . But more significantly, it is a different parameter! It is possible to calculate  $\alpha_L$  from OWL data:  $\alpha_L = \text{Im} \{ (\epsilon_r' - 1) - j 60 \sigma \lambda \}^{1/2}$ , in dB/m. It is also possible to infer  $\alpha_L$  from measured height-gain data near the air-vegetation interface. Self-consistent results were achieved for OWL data and height-gain measurements taken at Chumphon, Thailand.<sup>43</sup> An approximate expression for  $\alpha_L$  was deduced from OWL data:<sup>19</sup>

$$\alpha_L = 9 \times 10^{-3} f_{\text{MHz}} + 0.1, \text{ in dB/m } (6 \leq f_{\text{MHz}} \leq 75).$$

#### 6.2 Open-Wire Transmission Line Results

Data obtained with the open wire transmission line indicates that  $\epsilon_r'$  of a volume containing living vegetation is typically in the range 1.01 to 1.1,<sup>19</sup> with most samples nearer the lower end of the range. Dispersion is small for  $6 \leq f_{\text{MHz}} \leq 25$  and slight for  $25 \leq f_{\text{MHz}} \leq 75$ . The measured results for effective conductivity show a considerably greater variation with frequency (see Fig. 1).

#### 6.3 Electrical Parameters Inferred by Fitting Propagation Models

The radio propagation data obtained in Thailand by Jansky and Bailey<sup>44,45</sup> have been used by Sachs<sup>46</sup> and Hicks, et al,<sup>45</sup> along with propagation models, to infer electrical forest parameters. In each case ground (g) electrical parameters  $\epsilon_{rg} = 15$  and  $\sigma_g = 10 \text{ mho/m}$  were assumed. An attempt was made to obtain the best fit assuming the forest height and forest and ground electrical parameters were frequency independent. The results of these electrical comparisons for two sites in Thailand are summarized in Table 1 and compared with open wire line data taken at the same site. Muehe and Cartledge<sup>30</sup> have inferred  $\alpha_s$  (see 6.1.1) and  $\epsilon_r'$  values from antenna pattern measurements in U.S. forests. At about 400 MHz they inferred  $1.01 \leq \epsilon_r' \leq 1.02$ , with the higher value in more dense vegetation.

At about 1300 MHz the antenna pattern lobing was not distinct enough to permit an estimate of  $\epsilon'_r$ .

TABLE 1. COMPARISON OF THAILAND FOREST ELECTRICAL PROPERTIES

SITE	PAK CHONG, THAILAND			SATUN, THAILAND	
	Sachs	Hicks	OWL	Hicks	OWL
Freq. (MHz)	6-100	2-400	6-75	2-400	6-75
Forest Eff. Ht. (ft)	40	60	--	100	--
$\epsilon'_r$	1.02	1.01	1.02	1.01	1.01
$\sigma_H$ (mmho/m)	0.1	0.04	--	0.03	--
$\sigma_V$ (mmho/m)	0.15	0.05	--	0.04	--
$\sigma_{OWL}$ (mmho/m)*	--	--	0.02-0.13	--	0.01-0.10

\* Conductivity increases with frequency (see Fig. 1).

## 7. Relationship Between Electrical and Physical Properties of Vegetation

### 7.1 Biomass, Biodensity and Effective Forest Height

It is important to be able to relate the types of physical measurements made by foresters and botanists<sup>47-50</sup> to the electrical and physical properties of forests required for antenna and propagation calculations. Currently such relationships are not well worked out. The foresters measure tree-height distributions as well as the diameter of trees at breast height (4 ft). They relate the breast height diameter (BHD) to tree height and weight for a given species. They also compute the biomass of a forest area in tons per acre. The term biodensity was coined during the SRI work on this problem where biodensity is the weight per unit volume of the forest--a property that can vary with forest height. It is known that the electrical properties of materials are related to their density. Parker and Hagn<sup>17</sup> found that  $\epsilon'_r$  is a linear function of biodensity for freshly cut willows. It is possible to estimate an average effective biodensity for a forest considered as a slab by dividing the biomass by the effective forest height used in the slab model to fit measured basic transmission loss data. The Thailand sites of Pak Chong and Satun had biomass in tons per acre of approximately 130 and 202 respectively. The average effective biodensity computed using the effective forest height of Hicks<sup>45</sup> is the same for each site to within 10%. The basic transmission loss measured by Jansky

and Bailey was greater at Satun than at Pak Chong. However, the electrical properties at each site inferred by Hicks by fitting the slab model were very similar (see Table 1). Also, those measured with the OWL were quite similar for the two sites (see Fig. 1). Also, the results of Muehe and Cartledge<sup>30</sup> using an antenna pattern technique and of Reeve and Adams<sup>31</sup> using the wave-impedance method indicate the electrical properties of forests are a function of the density of the vegetation. It is possible that the combination of average effective bi-density (as might be estimated from OWL measurements and previously established relationships between bi-density and  $\epsilon_r'$  and  $\sigma$ ) and effective tree height (as may be determined by picking a point on the measured tree height distribution) are the properties required to infer the parameters required for the simplest propagation and antenna slab models. Some work is still required to be able to estimate the effective forest height from a tree-height distribution, however, the 80th percentile seems a reasonable estimator when no other guidance is available.

## 7.2 Remote Sensors

It might be possible to determine empirical relationships between the physical properties of forests, as determined by the types of remote sensors discussed in Ref. 36, and the forest electrical properties required for use in antenna and propagation modeling. For example, microwave radiometer brightness temperatures might give data on vegetation moisture which, in turn, might be empirically related to  $\epsilon_r$ .<sup>17,38</sup> Such relationships, if they exist, remain to be worked out.

## 8. Conclusions

### 8.1 Methods of Measurement

Fitting propagation data or antenna pattern measurement data to slab models appears useful for estimating  $\epsilon_r$  in the frequency range up to about 500 MHz. While the electrical properties obtained in this manner are not uniquely defined, they are directly useful in the same model used to derive them. Also, anisotropy can be inferred in this manner for  $\sigma$ .  $\alpha_s$  values can be obtained for much higher frequencies (e.g., SHF). The OWL probes when used with appropriate sampling techniques, do give unique values for the macroscopic electrical properties of vegetation. They are also useful for checking for homogeneity in a forest area both with height and with radial distance, but they are not useful for resolving anisotropy. The useful upper frequency limit for the OWLs used to date (in situ in forests) is 75 MHz. This could be extended to perhaps 150 MHz by careful refinement of the current techniques. The wave impedance technique should be useful for estimating  $\epsilon_r$  in the upper LF to lower HF range. The capacitor and cavity techniques hold some promise for use with freshly cut vegetation but they are not particularly useful for in situ measurements. The cavity technique is potentially useful for measuring the moisture content of freshly cut vegetation, and microwave attenuation through living vegetation is also quite sensitive to moisture content.

## 8.2 Macroscopic Electrical Properties

Field measurements are required to determine  $\epsilon_r$ . The most probable values for  $\epsilon_r$  are in the range 1.01 to 1.1 except in extremely localized dense spots where  $\epsilon_r$  might approach 1.5. More typical values of  $\epsilon_r$  are relatively independent of frequency above HF and are closer to 1.01 than to 1.1 as inferred from OWL data and model fits on propagation data.  $\epsilon_r$  is very dependent on the density and moisture content of the vegetation. The macroscopic conductivity observed with the OWL probes is a function of frequency, increasing approximately as  $f^{0.7}$  in the HF and VHF bands. It is possible through model parameter adjustment to find combinations of frequency-independent values of these parameters which provide reasonable propagation model fits to measure data over a range of several frequency decades (e.g., 2-200 MHz), and values for  $\sigma$  of 0.03 to 0.15 mho/m have obtained from HF and VHF data in Thailand forests.

## 8.3 Intrinsic Properties of Vegetation

The intrinsic conductivity of living vegetation is probably in the range 0.01 to 1.0 mho/m at HF and VHF and it probably increases with increasing frequency.<sup>19</sup> The work of Broadhurst<sup>33</sup> on the electrical properties of leaves indicates that  $\epsilon_r$  is a function of frequency, that it can be larger than 80, that it decreases with increasing frequency for the same samples. The loss tangent of these leaves decreases in the range 1 MHz to 1 GHz from about 10 to 0.1, but this decrease is not monotonic.

## 9. Recommendations

- Empirical relationships between forest physical and electrical properties should be further developed, particularly as they relate to the slab model. The relationship between biomass, biodensity and effective forest height should be better defined by field measurements. Methods for determining effective forest height from a tree-height distribution need refinement, and variation of forest effective height with frequency need to be explored. The utility of the method for estimating  $\epsilon_r$  based on the equivalent circuit of a single tree near an OWL<sup>11</sup> should be checked.

- Methods of measurement of  $\epsilon_r$  need to be extended and tested. The OWL probes should be extended in frequency, and probe design and sampling rules should be further optimized as a function of vegetation type and density. The wave impedance method should be perfected, and the results obtained should be compared with data from the same site(s) obtained with OWL probes and from slab model fits to measured propagation data. Additional techniques should be sought for measurement of forest anisotropy. Remote sensing methods of estimating  $\epsilon_r$  should be investigated.

- Additional data on forest electrical parameters should be obtained, especially below 6 MHz and above 100 MHz. The upper useful frequency for the slab model needs to be better defined. OWL data as a function of height in a forest should be obtained. Analytical models should be run to better define the accuracy required for  $\epsilon_r$  data.

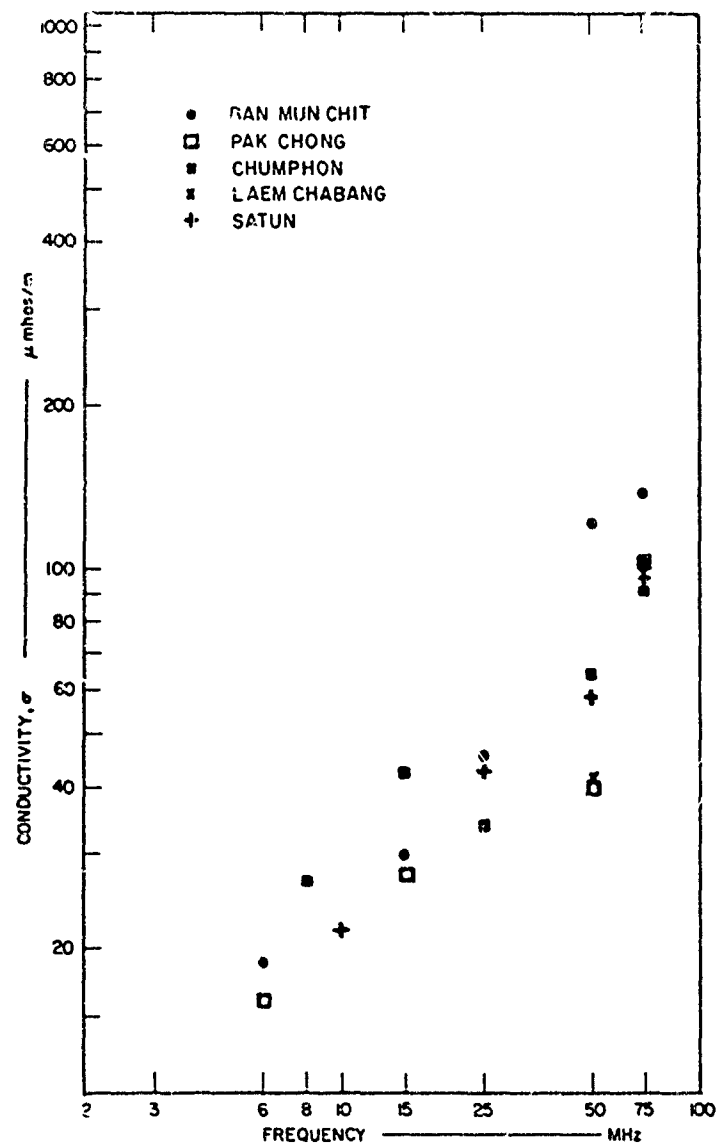


Figure 1 Macroscopic Effective Forest Conductivity Versus Frequency from OWL Measurements at Five Sites in Thailand (From Ref. 18).

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RADAR PROPAGATION MEASUREMENTS

by

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Presented at

Workshop on Radio Systems  
in Forested and/or Vegetated Environments  
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## RADAR PROPAGATION MEASUREMENTS\*

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During the period 1967 to 1972 Lincoln Laboratory was actively engaged in research and development of foliage penetration radars. The objectives were to detect moving vehicles and personnel at as long a range as possible, both from ground-based and airborne radars.

During this period several experimental radars were developed including a helicopter-borne truck detector and ground-based radars with various ranges. The most successful was the Camp Sentinel Radar, a ground-based, foliage penetration radar first deployed in SEA in 1968. Several were later built by the Army's Harry Diamond Laboratory and saw service until the end of the hostilities. The research and development work is well documented. A bibliography is available.

In this paper we will discuss the results of several field measurement programs whose aim was to obtain a better understanding of the physical principles needed to sensibly engineer a modern, foliage penetration radar.

Most of the results presented here are from a field program in the Florida Everglades which lasted more than a year. Two radars, one at UHF and one at L-band, were employed. Their characteristics are shown in Table I. In each radar linear, large-dynamic-range samples of the quadrature video output were taken using sample-and-hold circuits. These were digitized and recorded on magnetic tape. The tapes were returned to the Laboratory and processed using a large computer.

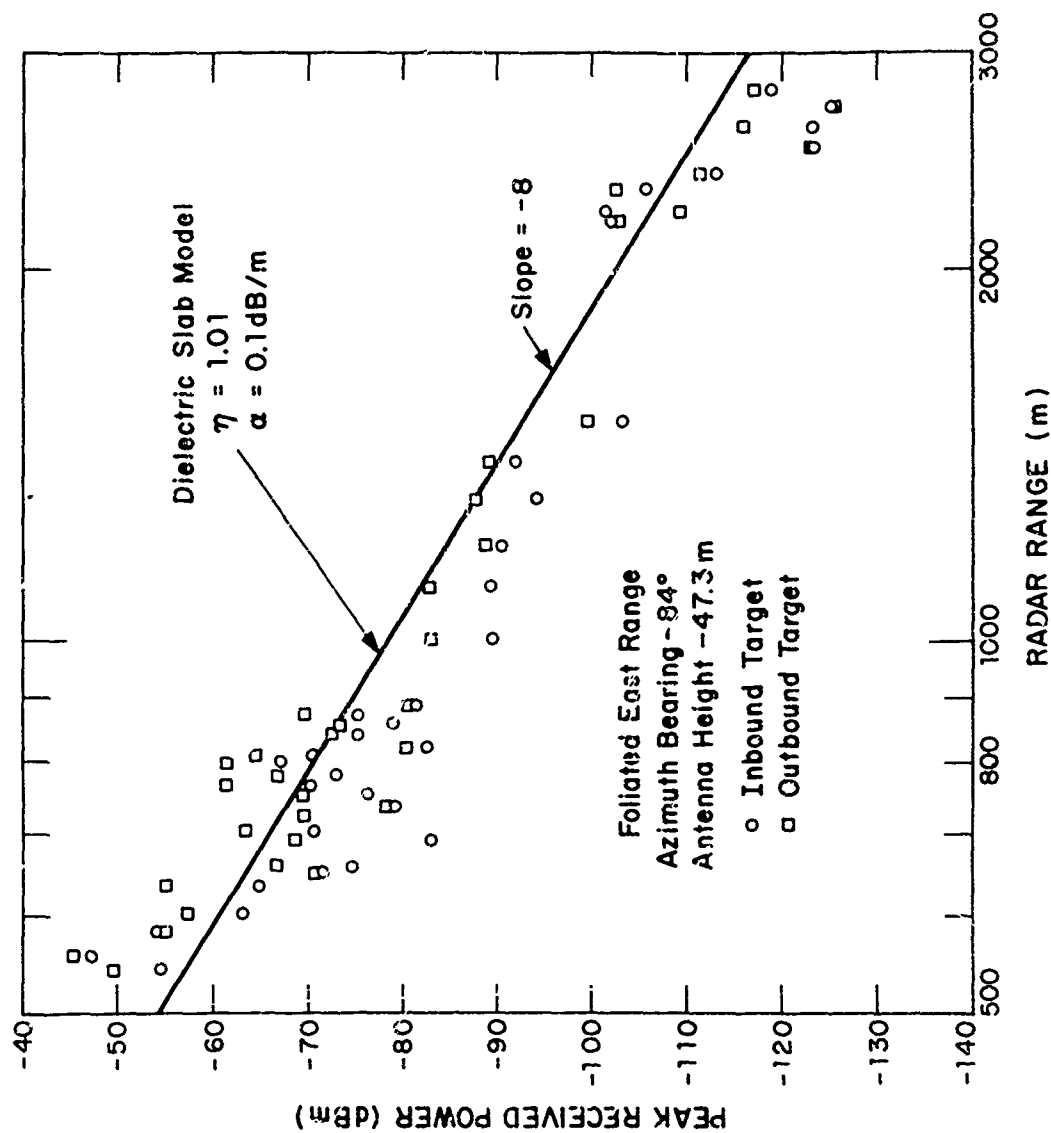
In an effort to verify the popular lossy dielectric slab model for propagation into a forest, the UHF radar was used to measure the peak power received from a moving target in a uniform flat stand of pine trees. The antenna was well above the tree tops so the waves were diffracted into the forest. The results are shown in Figure 1 where a theoretical curve has been drawn assuming certain values for the index of refraction  $n$  and the loss  $\alpha$ . An independent measurement of loss value in the same trees agreed well with the value used in Figure 1. Notice that the signal fell off as  $R^{-5}$ . The slab model predicts a one-way power loss proportional to  $R^{-4}$  so good agreement was obtained. There was considerable scatter in the data due to local reflections, but the scatter in any region was directly proportional to the mean level in that region.

\*This work was sponsored by the Department of the Air Force and the Advanced Research Projects Agency.

TABLE I

RADAR SYSTEM PARAMETERS

	<u>UHF</u>	<u>L-Band</u>
I TRANSMITTER		
Peak Power (kW)	20	3
Pulse Width (nsec)	35	35
Nominal Prf (kHz)	30	30
II RECEIVER		
Bandwidth (MHz)	35	35
Noise Temperature (°K)	1000	1200
Number of Range Gates	10	10
Range Gate Width (m)	5.2	5.2
Range Gate Spacing (m)	15	15
III ANTENNA		
Type	2 × 8 array	1 × 16 array
Polarization	horizontal	horizontal
Beamwidth (deg)	14	5
Available Gain (dB)	18	19
Amplitude Taper	linear	"cosine"
IV RANGE PERFORMANCE (no foliage)		
Target Sigma (m <sup>2</sup> )	0.5	0.5
Target Height (m)	1.78	1.78
Integration Gain (dB)	44	44
Typical Range for +14 dB S/N (km)	5.6	4.8



RETURN TARGET POWER AS A FUNCTION OF RANGE

Figure 1

Further verification of the slab model at UHF was obtained by making vertical field probe measurements. A receiving antenna was gradually raised from ground level up to the tree tops. The variation in field strength including the reinforcements and nulls due to ground reflections was observed to be in fair agreement with the lossy slab model. At L-band similar vertical field probe measurements agreed in average value with the slab model, but the nulls were generally filled in by local random reflections.

The radar return from the trees (clutter signal) was measured also at UHF as a function of radar range (Figure 2) again using a uniform stand of pine trees. The mean clutter return clearly falls off as  $R^{-7}$ . Since the total return from a range-azimuth cell is the sum of the signals from all the trees in that cell, the total power should vary as it would for a single scatterer,  $R^{-8}$ , multiplied by the size of the range-azimuth resolution cell. The size of a cell increases linearly with range since its cross-range dimension is fixed by the azimuth beamwidth. Thus, the  $R^{-7}$  law results.

The two graphs, Figures 1 and 2, are evidence that the mean target-to-clutter ratio falls off only linearly with range so that the required sub-clutter visibility is not a strong function of range. The radar target-to-noise ratio however falls off as  $R^{-8}$  so considerably more radar sensitivity is required compared to the same target without ground or forest effects.

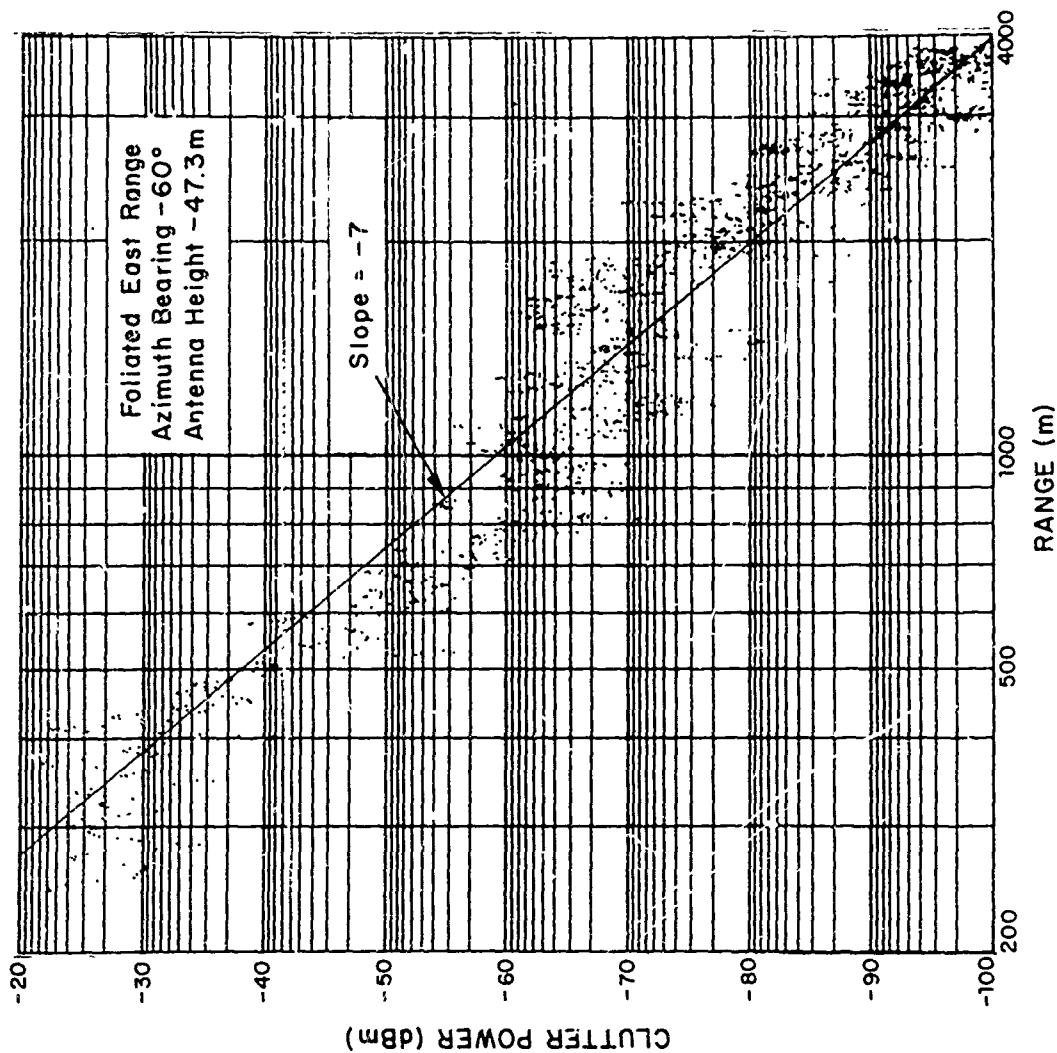
Of great interest to the radar designer are the shapes of the spectra of the target and clutter returns. The shape of these spectra determine the optimum type of signal processing to be used to extract the target signal from the clutter.

Figure 3 is the spectrum of a man walking toward the UHF radar. Notice the fine detail obtained. The subject walked through a 17-ft. deep range gate 10 times at a carefully controlled velocity. The spectrum shown averages these 10 runs. One can distinguish his step frequency and even his dissymmetry from side to side as reflected in his two-step frequency return. These were in excellent agreement with his measured velocity and step size. The leakage line at -3.5 Hz is instrumental and was due to an unbalance in the quadrature video detectors employed.

The spectrum of the same man walking in the woods is shown in Figure 4. The step motion is still discernible but the spectrum has been greatly smeared due to multipath effects. Also to be observed is a relatively small clutter return at zero frequency.

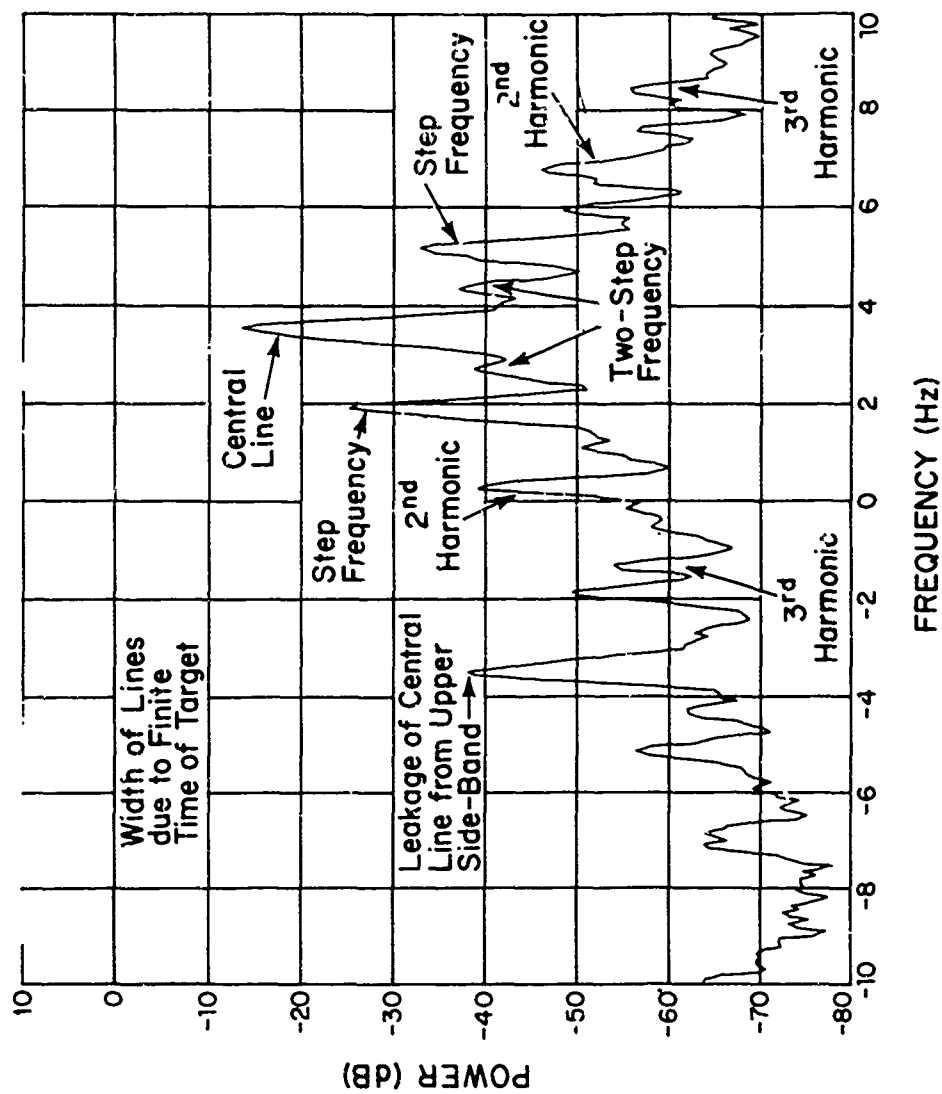
The spectrum of the signals returned from trees blowing in the wind is shown in Figure 5 for two frequencies. A theory has been worked out to explain these spectra.

A tree is regarded as a damped oscillator excited by the wind. The tree has a natural resonant frequency of about 0.3 Hz which accounts for the



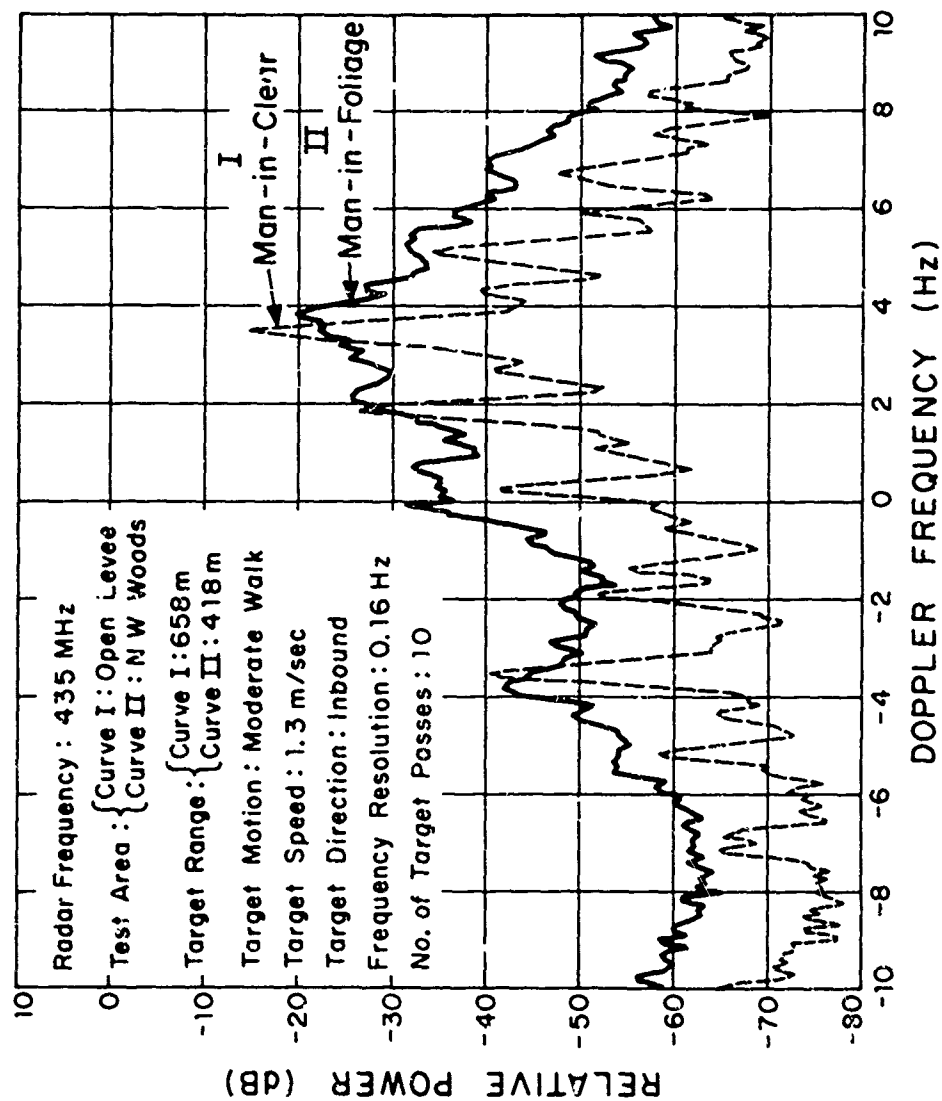
CLUTTER RETURN AS A FUNCTION OF RANGE

Figure 2



Spectrum of Man Walking Toward Radar (435 MHz)  
Speed 1.3 m / sec

Figure 3



MOVING-TARGET SPECTRUM

Figure 4

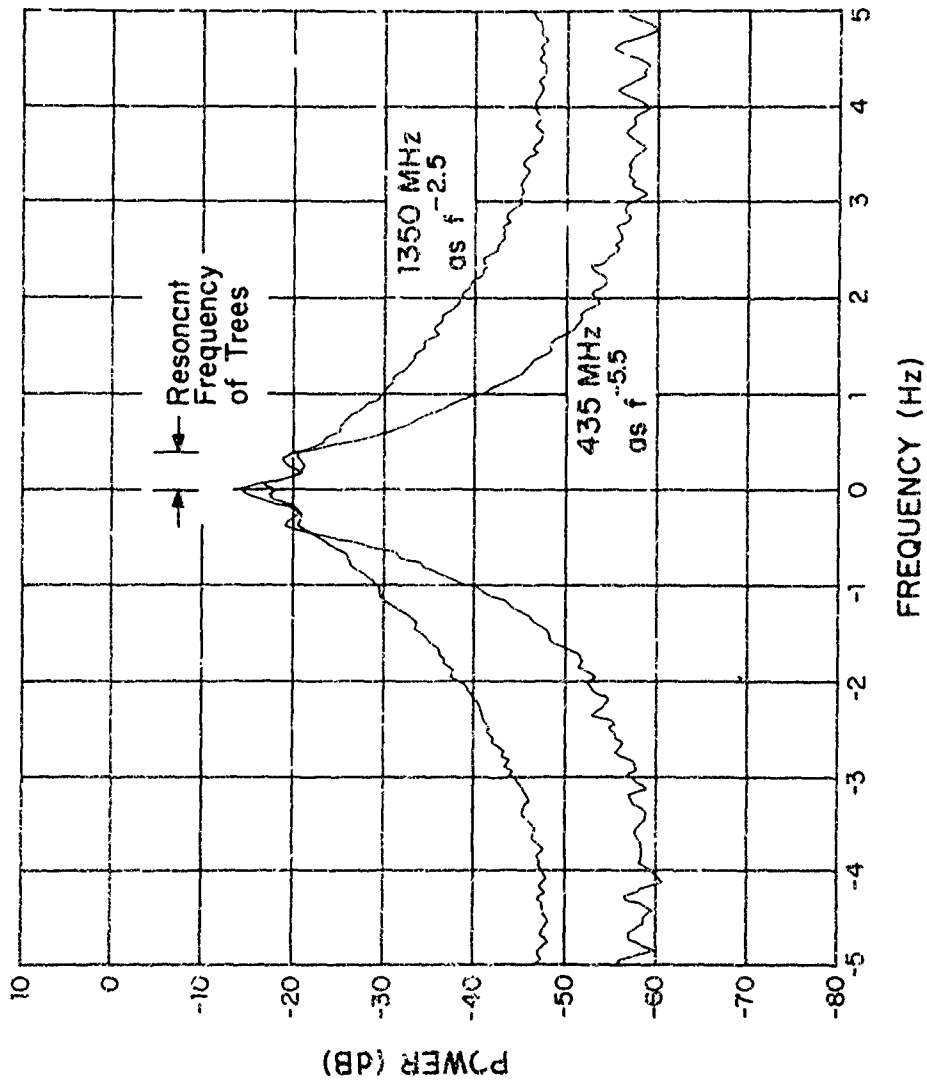
small peaks in both spectra at this frequency. Wind turbulence is known to have an  $f^{-5/3}$  power spectrum. When this driving force excites a resonator away from resonance, a  $-4 -5/3$  or  $-5.67$  power law should apply for the spectrum of the motion of the tree.

Now at UHF the tree movement is small compared to a wavelength so that this motion is converted to a spectrum of phase modulation which closely approximates its motion spectrum until it reaches the noise level at  $-57$  dB. The spectrum is that of a phase modulated oscillator with a low index of modulation.

At L-band the index of modulation is three times higher so the further out sidebands are excited and the spectrum falls off more slowly. A complete theory for this phenomena has been worked out and agrees very well with measured results.

A further confirmation was obtained by directly measuring the spectrum of motion of a single tree blowing in the wind and obtaining results almost identical to the UHF spectrum in Figure 5.

Almost all the elements necessary to predict the performance of foliage penetration radars at UHF and L-band have been measured and agree with physical models. The one big exception is the relation of refractive index and loss in the forest to the forest parameters such as tree diameters and densities. It is hoped that a good theory for this relationship will be forthcoming in the near future.



Comparison of UHF and L-Band Forest Clutter Spectra

Wind ~ 10 - 15 mph

Figure 5

UNCLASSIFIED  
LIST OF PUBLICATIONS

RADAR TECHNIQUES GROUP  
M. I. T. LINCOLN LABORATORY

(available from N.T.I.S. if AD number is shown)

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SUMMARY OF PATH LOSS MEASUREMENTS  
AND JUNGLE CHARACTERISTICS

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Presented at

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## SUMMARY OF PATH LOSS MEASUREMENTS AND JUNGLE CHARACTERISTICS

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### 1.0 INTRODUCTION

Little was known about radio propagation in tropical forest environments in the early 1960's. Practical communications experience in tropical environments during WW II and the analysis by Herbstreit and Crichlow<sup>1</sup> of associated experimental data, however, showed that communications at HF and VHF were severely attenuated and dependent upon the forest characteristics. The data were too sparse to be definitive. Thus, the Advanced Research Projects Agency (ARPA) initiated project SEACORE (South-east Asia Communications Research) to deal specifically with radio communication in tropical environments. As a part of this project, under contract with ARPA and technical direction of the U.S. Army Electronics Command (ECOM), Atlantic Research Corporation conducted an extensive research program on radio wave propagation in tropical environments.

The major objective of the tropical propagation research program was to quantitatively define the propagation and environmental factors governing tactical radio communications in such environments. The experimental test areas were two characteristically different tropical forests of Thailand. The environmental measurements encompassed terrain, vegetation, indigenous radio noise, and climatological factors of temperature, rainfall, wind, and atmospheric refractive index. The radio propagation measurements encompassed frequencies from 0.1 MHz to 10 GHz; propagation paths of ground-to-ground, air-to-ground and mixed vegetation-clearing; linear aligned and nonaligned polarizations; ranges up to 30 miles; antenna heights from ground to above foliage; and CW and wideband signal transmissions. Analyses were conducted to obtain the median path loss and probability functions related to the spatial and frequency fading of the signals as a function of environmental and system parameters.

The experimental equipments, procedures, environmental and propagation data, analyses, and theoretical works have been presented under the original contract in seven Data Bulletins, twelve Semiannual Reports and four Final Report Volumes. Select portions of the data have also been applied by other researchers in establishing theories. Their works and elements of the data and results have been discussed in a recent summary of project SEACORE.<sup>2</sup> In keeping with the objectives, time and space of the Workshop, this report is limited to a summary of the scope and general results of the program conducted by Atlantic Research. Reference is made to the appropriate reports for details and areas are suggested for further investigation.

### 2.0 ENVIRONMENTAL DESCRIPTION

A major objective of the tropical propagation research program was to derive a method or methods whereby propagation could be predicted for general tropical forested environments. Propagation and environmental measurements were conducted in two characteristically different tropical environments, called Area I and Area II.\*

\* Special propagation and environmental measurements were also conducted in a third environment of bamboo growth, about 100 miles south of Bangkok, near Sattahip, Thailand, for the purpose of studying propagation at frequencies of 550 MHz to 10 GHz.<sup>3,9</sup>

Area I, which provided a propagation range of about 30 miles over relatively rough terrain, can be broadly classified as a wet-dry semievergreen forest (monsoon tropical climate) and was located some eighty-five miles north of Bangkok, Thailand.<sup>3,4,5,6,7,8,9</sup> Area II, which provided a propagation range of about 6 miles over relatively smooth terrain, can be broadly classified as a tropical rain forest area (rainy, tropical climate) and was located about 525 miles south of Bangkok, Thailand.<sup>10,11,12,13,14,15,16</sup> Table 1 summarizes a number of climatological factors for Areas I and II.<sup>13,9</sup> The rainfall is perhaps the most distinctive difference in the climatological factors, with it being significantly larger in Area II than Area I.

TABLE 1  
CLIMATOLOGICAL COMPARISON BETWEEN AREA I AND AREA II

		<u>Annual Average</u>	<u>Monthly Average</u>	<u>Monthly Median</u>	<u>Standard Deviation</u>
AREA I (Wet-Dry, Tropical)	Temperature (°F)	80.7	80.7	81.3	3.5
	Rainfall (in.)	52.6	4.4	2.7	3.8
	Relative Humidity (%)	67.53	67.53	68.2	6.6
	Relative Refractive Index (K)	1.502	1.502	1.521	0.045
AREA II (Rainy, Tropical)	Temperature (°F)	84.2	84.2	84.7	1.4
	Rainfall (in.)	97.2	8.1	6.75	6.5
	Relative Humidity (%)	74.04	74.04	76.0	6.9
	Relative Refractive Index (K)	1.621	1.621	1.620	0.055

The most significant natural environmental factors influencing tropical propagation in the 0.1 MHz to 10 GHz range of frequencies examined are apparently the terrain and vegetation. This is not to imply that such factors as rainfall, atmospheric refractive index and others do not influence tropical propagation in general but rather that the terrain and vegetation influences were apparently dominant over the vegetated paths. The terrain profiles over the propagation paths of Area I are given in reference (9) and of Area II in references (11) and (12).

The tropical vegetation is composed of trees, broad-leaved plants, vines and other undergrowth. The trees, however, appear to be the more significant vegetative influence on radio propagation. A summary of the forest characteristics of Areas I and II is given in Table 2. The height, diameter and density of the trees in Area II are larger than those in Area I and, as mentioned later, these factors grossly correlate with propagation characteristics of the two environments. A satisfactory method of predicting radio propagation from known characteristics of the forest, however, has not been determined. In the author's opinion, this is one of the more significant areas that requires further work.

TABLE 2  
SUMMARY OF FOREST CHARACTERISTICS OF AREA I AND AREA II

<u>Forest-Characteristics</u>	<u>Area I<sup>8</sup></u>	<u>Area II<sup>10,14</sup></u>
Tree Density (trees/acre)	362	606
Tree Height (meters)	50% < 10 m 90% < 20 m	50% < 18 m 90% < 30 m
Tree Diameter at Breast Height (meters)	50% < 0.1 m	50% < 0.24 m
Biomass (tons/acre)	130	309 (202)

### 3.0 RADIO WAVE PROPAGATION MEASUREMENTS

The propagation measurements were directed primarily toward obtaining the basic transmission loss over tropical vegetated paths as a function of operational and environmental parameters. The great majority of propagation measurements were made with CW transmissions. During the final phases of the program, however, pulse and swept frequency measurements were made to determine multipath characteristics of the tropical vegetated channel. For convenience, the narrowband and wideband measurements are discussed separately with further subdivision of the narrowband measurements as well.

#### 3.1 NARROWBAND MEASUREMENTS

Narrowband (CW) radio propagation measurements were made in Areas I and II. Standard antennas and calibrated systems were employed.<sup>8,11</sup> The resultant propagation data were reduced to "basic transmission loss" which gives the path loss relative to isotropic antennas. The major frequencies employed in Area I were 0.105, 0.30, 0.88, 2, 6, 12, 25, 50, 100, 250, 400 and 550 MHz and 1, 2.5, 5.5 and 10 GHz. The same frequencies, except that 0.105, 0.3 and 6 MHz were eliminated, were utilized in Area II.\*

For frequencies below 2 MHz, only vertical polarizations were employed. Both horizontal and vertical polarizations were employed at 2 MHz and above.

The most widely employed procedure for making propagation measurements with ground based terminals was to fix the transmitting antenna at a prescribed height and polarization and transmit at a fixed frequency. The receiving antenna (with polarization generally aligned with that of the transmitting antenna)† was raised in 5 to 6 foot increments, at a specified range, from near ground to above the foliage. The received median field strength over each 5 to 6 foot increment of receiver antenna height was recorded. This resulted in one set of propagation measurements as a function of receiving antenna height for a specific frequency, polarization, range and transmitting antenna height. The procedure was repeated for different frequencies, transmitting antenna heights, polarization and at different ranges until, generally, measurements were made for all combinations of the selected variables. In addition to the fixed range measurements, continuous recordings of received field strength along the roads and trails were also made with the receiving antenna (either vehicle mounted or hand carried) at a height of about 6 feet.

The resultant basic transmission loss data were subjected to various analyses. These cannot be discussed in detail here but some general results will be summarized. It will be convenient to further separate these into broad frequency ranges.

##### 3.1.1 Propagation at Frequencies of 0.1 MHz to 1 MHz

a) At propagation ranges beyond the induction field of the antenna, the tropical vegetation apparently has no discernible effect upon the basic transmission loss for vertically polarized energy received with a small loop antenna (horizontal polarization was not examined in this frequency range.)<sup>9</sup> Electrically short antennas may, however, be influenced by trees in close proximity to the antenna.

\* Some limited special measurements at other frequencies within the range of the general frequencies were employed in both areas.<sup>9,17</sup>

† Some special tests were also conducted at various combinations of linear polarizations.<sup>9,13</sup>

b) The median basic transmission loss appears to behave as the surface wave over terrain without vegetation.<sup>9</sup>

c) The variations of basic transmission loss (in dB) with range appear to be normally distributed (i.e., field strength is log-normally distributed).<sup>8</sup>

d) The median basic transmission loss showed no significant differences between the wet and dry seasons (i.e., climatic effects appear to be negligible).<sup>9</sup>

e) The atmospheric noise levels appear to be the same with antennas submerged in the vegetation as for antennas elevated above the vegetation.<sup>9</sup>

### 3.1.2 Propagation at Frequencies of 2 MHz to 400 MHz

a) The median basic transmission loss increases exponentially with distance in the foliage from near the antenna to ranges of about 1000 feet.<sup>12</sup> At ranges greater than approximately 1000 feet, the median basic transmission loss increases with distance as  $40 \log_{10}(\text{distance})$ , the loss decreases with increasing antenna height (or decreasing thickness of vegetation above the antenna) in the vegetation, and increases with increasing frequency.<sup>9</sup> A number of empirical models have been developed to account for this general behavior to include the variations in the propagation caused by gross terrain features.<sup>9,2</sup> The effect of the vegetation was included as an empirical factor, however, and was not well understood until the work by Sachs and Wyatt,<sup>18</sup> Sachs,<sup>19</sup> Tamir,<sup>20</sup> Wait,<sup>21</sup> and Dence and Tamir<sup>22</sup> showed the median basic transmission loss to be described by the lateral wave mode of propagation. The model for this mode of propagation in vegetated environments treats the vegetation as a uniform, homogeneous, dissipative slab bounded above by air and below by ground. The lateral wave mode is discussed by Tamir<sup>23</sup> and Sachs<sup>24</sup> in the Workshop proceedings. The model parameters specifically related to the environment are the slab thickness (related to vegetation height) and the effective permittivity and conductivity of the slab (vegetation) and ground. Estimates of these model parameters can be obtained by fitting theoretical results to propagation data. The conductivity appears to be the most critical and the sets of parameters are not unique.<sup>17</sup> Estimates of model parameters for Area I obtained by Sachs and Wyatt<sup>18</sup> differ from those obtained by Hicks et al.<sup>17</sup> The differences may be attributed to the upper limit of frequency employed (Sachs and Wyatt used 100 MHz and Hicks et al. used 400 MHz) and to the general nonuniqueness of a set of slab parameters.

Differences were also obtained in the slab parameters for Areas I and II. The effective slab height and conductivity were larger for Area II than for Area I, as would intuitively be expected due to the taller and more dense vegetation of Area II.<sup>17</sup> The model parameters were derived from comparison of theoretical results with experimental propagation data, and to the author's knowledge there is no method for quantitatively relating the slab parameters to environmental factors. A nonhomogeneous dissipative slab model has been suggested and theoretically investigated as an aid in obtaining such a relation,<sup>17</sup> but it has not been compared with experimental data.

A comparison between the measured median basic transmission loss as a function of frequency and antenna height for Areas I and II is given in Figures 1 and 2 for vertical and horizontal polarization, respectively. The data shown were normalized to one mile by the distance dependence of  $40 \log(\text{distance})$  and represent averages over wet and dry seasons and many roads and trails. An extensive tabulation of such data for Areas I and II is available.<sup>15</sup>

b) The median basic transmission loss is generally larger for vertical polarization than horizontal polarization, with the difference decreasing as the antenna height in foliage increases and as frequency increases. Figures 3 and 4 show the difference in basic transmission loss for horizontal and vertical polarization as a function of frequency and antenna heights for Areas I and II, respectively.<sup>15</sup>

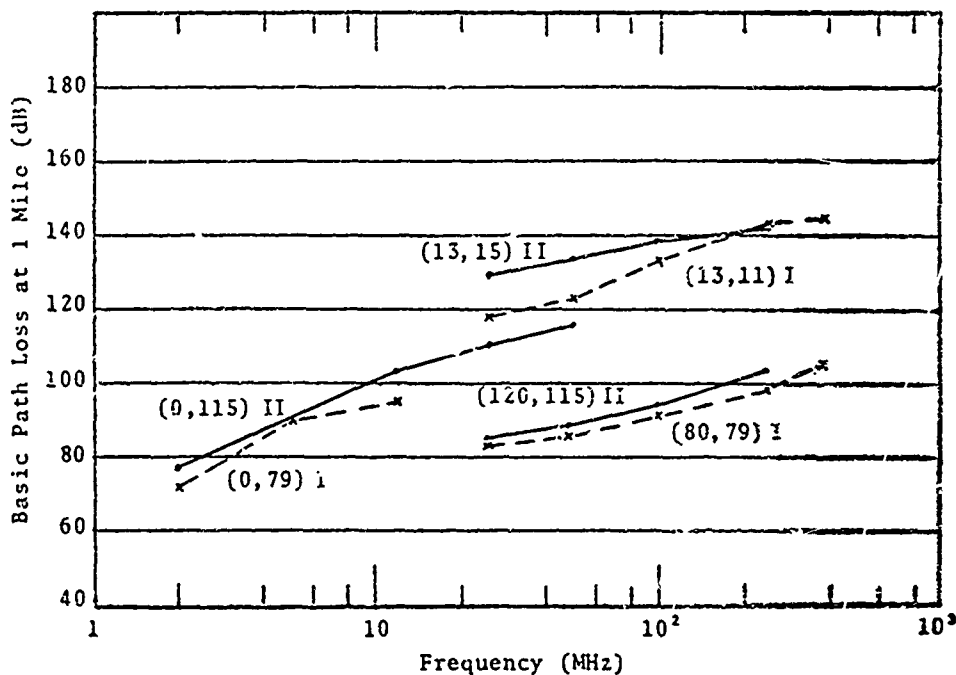


Fig. 1 Basic path loss for vertical polarization in Areas I and II as a function of frequency and antenna height. Nomenclature pertains to transmitting T and receiving R antenna height in feet and Areas I or II as (T,R) I.

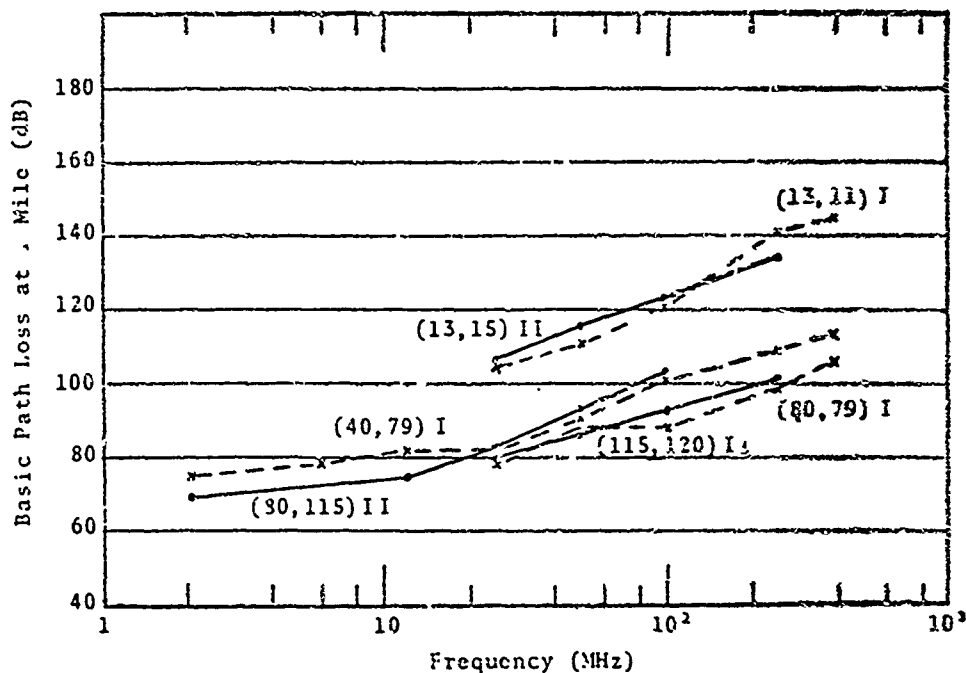


Fig. 2 Basic path loss for horizontal polarization in Areas I and II as a function of frequency and antenna height. (Nomenclature same as for Fig. 1).

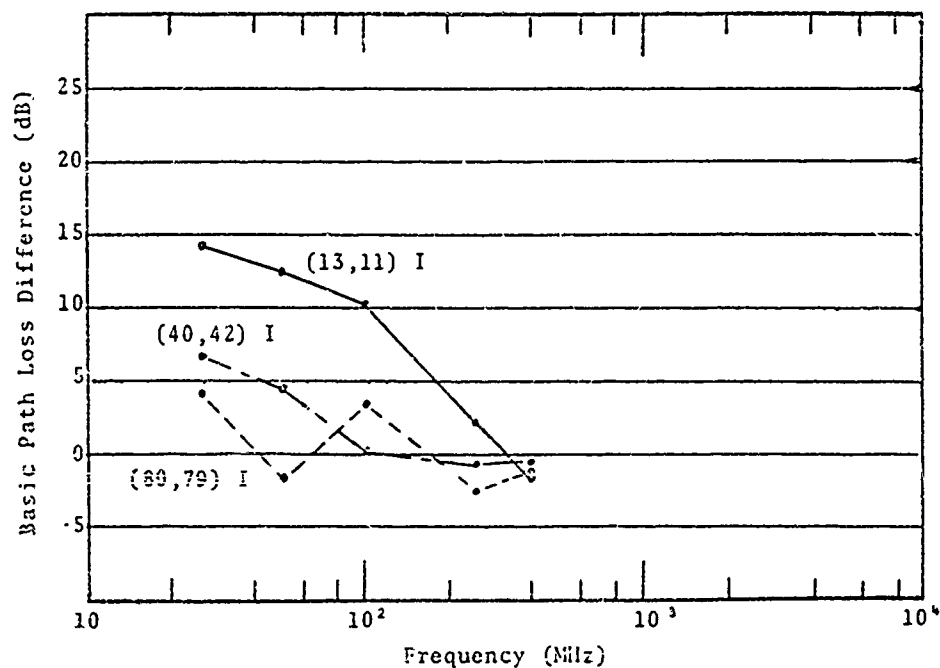


Fig. 3 Difference in basic transmission loss between horizontal and vertical polarization (vertical minus horizontal) as a function of frequency and antenna heights for Area I.

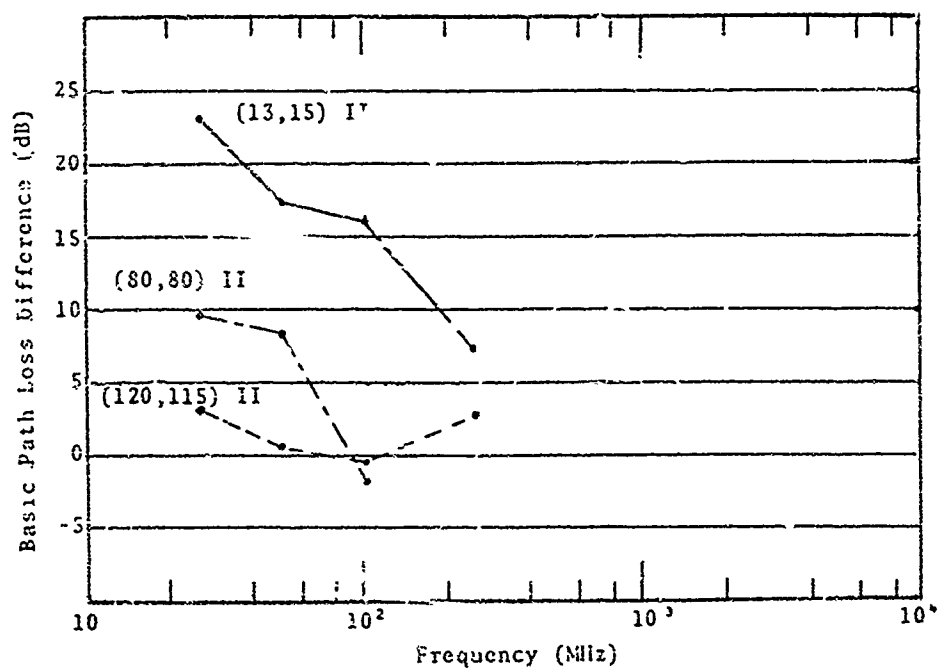


Fig. 4 Difference in basic transmission loss between horizontal and vertical polarization (vertical minus horizontal) as a function of frequency and antenna heights for Area II.

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c) There is no significant statistical difference between the basic transmission loss during wet and dry seasons.<sup>9</sup>

d) The atmospheric noise levels, for the frequencies below 50 MHz (the noise was not measured for frequencies greater than 50 MHz), appear to be the same for antennas submerged in the vegetation as for antennas elevated above the vegetation.<sup>9</sup>

e) The variations in basic transmission loss with distance generally have a long and short spatial fading character. The long spatial variations appear to be log normally distributed.<sup>8,16</sup> The short spatial fading, which is evident at frequencies greater than 25 MHz, is (at least for frequencies of 50, 100 and 150 MHz) generally Rayleigh distributed for vertical polarization and Rician distributed for horizontal polarization.<sup>16</sup>

f) The short spatial fading with distance has a quasi-cyclic character with an average period of 0.74 wavelengths.<sup>9,16</sup>

g) The average peak-to-minima ratio for the short spatial fading increases with frequency and is larger for vertical than for horizontal polarization. The individual peak-to-minima ratios may exceed 20 dB.<sup>9</sup>

### 3.1.3 Propagation at Frequencies of 0.550 MHz to 10 GHz

Propagation measurements at frequencies from 0.550 MHz to 10 GHz were made in Areas I and II. The primary purposes were to determine the attenuation rate through the vegetation, examine the concept of an optimum elevation angle for transmitting or receiving the lateral wave, to examine diffraction over a vegetated obstacle and to determine the influence of the vegetation on the antenna pattern. Other factors such as diurnal fading, time variability, and polarization effects were also examined.

a) The diffraction tests were performed in Area I and the results indicate good agreement, for the particular path obstacle, with theoretical results of a perfect knife edge with the top of the foliage constituting the obstacle edge as opposed to the terrain.<sup>9,10</sup>

b) The attenuation rate generally increases as frequency increases. The attenuation rate is shown in Figure 5 for Area I and a bamboo growth.<sup>9</sup>

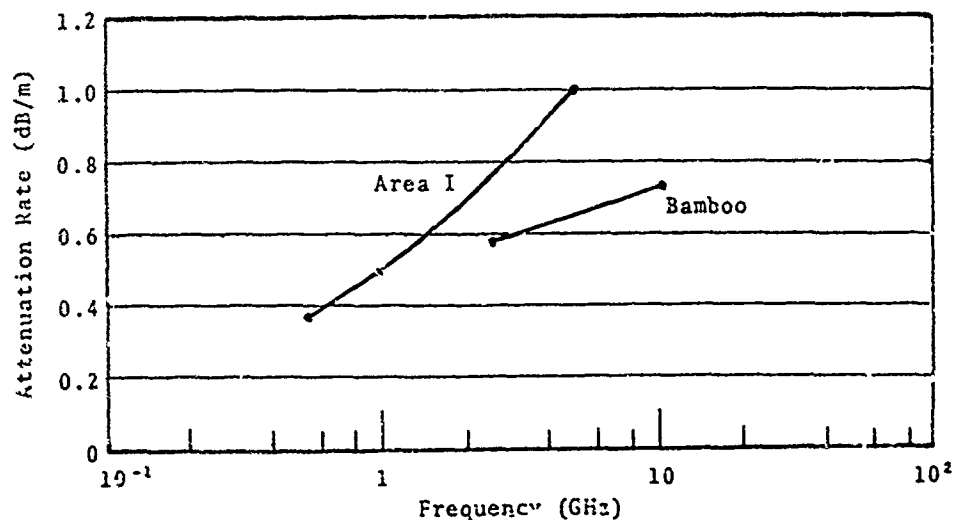


Fig. 5 Average attenuation rate as a function of frequency for Area I and a bamboo growth. Averages taken over both polarizations and antenna heights of 9 and 21 feet.

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6550

- c) The attenuation rate generally increases with decreasing antenna height.<sup>13</sup>
- d) The time variability of the basic transmission loss is correlated with the wind velocity.<sup>9</sup>
- e) The optimum elevation angle for transmitting and receiving antennas appears to depend upon the physical location of tree tops in the vicinity of the antennas.<sup>9</sup>
- f) Diurnal changes in the median basic transmission loss were apparently insignificant.<sup>9</sup>

### 3.2 WIDEBAND MEASUREMENTS

Pulse and swept frequency propagation measurements were made in Area II to determine the frequency selective character of a tropical forested environment. The measurements were generally made at 50, 100 and 150 MHz, using both horizontal and vertical polarizations, with transmitting antenna heights to 120 feet and receiving antenna heights from 6 to 40 feet.

The pulse measurements were largely qualitative but clearly showed that pulses are distorted by the multipath forest channel. The severity of the pulse distortions was maximum at positions of field strength minima (i.e., at the minima of the standing waves). Wind-induced foliage motion causes signal variations which are largest when the receiver antenna is located at a minima of the standing waves. For the receiver located in a clearing or on a hill, the pulse distortions are smaller than those obtained with the receiver located in the foliage.<sup>25</sup>

The swept frequency measurements were made to obtain more quantitative information than afforded by the pulse measurements. The frequency was swept over (usually) a 4 MHz band about the center frequencies of 50, 100 and 150 MHz (and a limited number at 400 MHz) and the amplitude and relative phase of the received signal were recorded as a function of the swept frequency. The procedure was repeated with the receiver positioned at different incremental ranges (usually 0.1 wavelength) and in different types of foliage.

The resultant data were analyzed to determine the frequency and spatial correlation functions. Figure 6 is an example of the frequency correlation functions of the envelope data. Using the customary  $1/e$  point as the coherent bandwidth, it was found that the coherent bandwidth of the forest channel, averaged over frequency, locations in the forest, polarization and different antenna heights, is 0.39 MHz.<sup>17</sup> This implies that a bandwidth about an order of magnitude smaller than this number may be transmitted with little or no frequency selectivity. The coherent bandwidth is also the order of magnitude of the frequency separation required for effective frequency diversity in the environment.

Examples of the spatial correlation functions are shown in Figure 7. Note the similarity of the radial and transverse correlation functions with vertical polarization and their dissimilarity with horizontal polarizations, which can be attributed to the receive dipole antenna patterns.<sup>17</sup>

The multipath intensity profile, which is the Fourier transform of the complex frequency correlation function of the channel transfer function, was computed from the swept frequency data for several field points and parameter configurations. The multipath intensity profile gives the distribution of the relative intensity of the multipaths as a function of their delays relative to a steady component in the present case. Figure 8 is an illustration of the multipath intensity profile. The intensity profiles showed that the multipaths of greatest intensity have an average delay  $\tau = 0.25 \mu\text{sec}$ .<sup>17</sup>

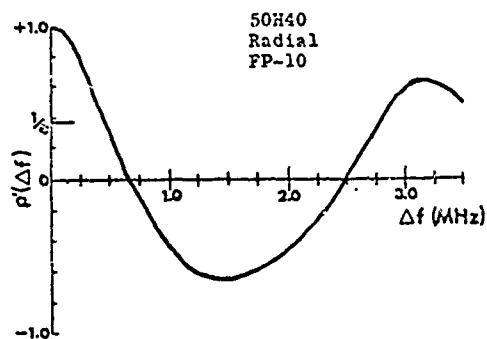


Fig. 6 Frequency correlation functions of the envelope. Legend "50H40" refers to frequency in MHz, polarization (horizontal), and transmitting antenna height in feet, respectively. "Radial" and "Transverse" refer to receiving antenna (height = 6 feet) motion relative to the direction to the transmitter. FP-10, Y-20, etc. refer to experimental field points.

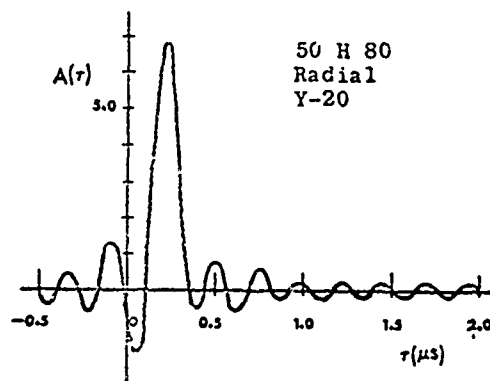


Fig. 8 Multipath intensity profile. Legend identified in Fig. 6.

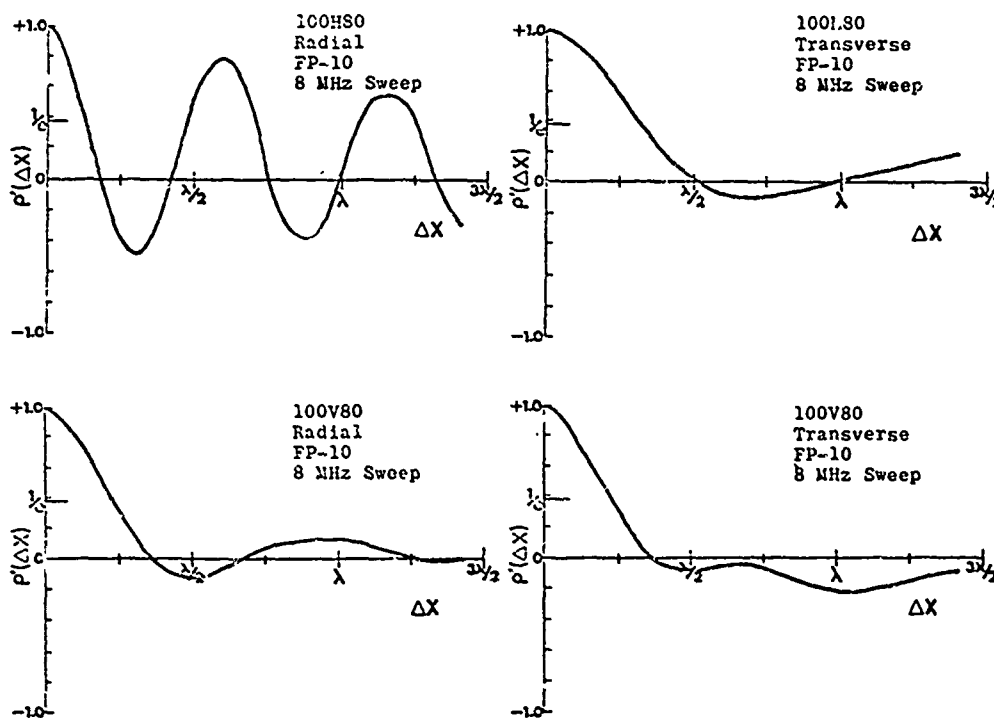


Fig. 7 Spatial correlation functions of the envelope. Legend identified in Fig. 6.

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STATISTICAL MODELING  
OF JUNGLE PATH LOSS DATA

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## Statistical Modeling of Jungle Path Loss Data\*

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### ABSTRACT

From 1962 to 1972 under Project SEACORE, the Advanced Research Projects Agency and the U.S. Army Electronics Command, have supported investigations and measurements in Southeast Asia and the United States to improve communications-electronics system performance in heavily forested environments. The present paper deals with one aspect of these investigations, namely, statistical characterization of path loss data. Experiments to collect path loss information were performed in Thailand and covered the frequency range 100 kHz to 10 GHz encompassing different locations, polarizations, seasonal rainfall variations to include a wide range of antenna heights (transmitting and receiving).

In our paper, we restrict the analysis to answer specific questions utilizing selected path loss data in the 2-400 MHz range where it is shown the propagation data exhibits strong random fluctuations and deterministic equations do not properly describe the statistical character. In addition, we relied solely on statistical modeling to account for these fluctuations and non-parametric statistical techniques were employed to analyze the data for specific configurations of transmitter and receiver height, distance, frequency and polarization. Techniques to predict path loss by examining the jungle as a random medium utilizing Maxwell's curl equations are mentioned.

Extensions to the present analysis are discussed and are related to determining transmission reliability aspects of concept formulation, feasibility determination and engineering design of communications-electronics equipment and systems.

### Introduction

In recent years extensive investigations and measurements have been made in Southeast Asia and the United States to determine the communication conditions that exist in forest environments. Studies were initiated in 1962, sponsored by the Advanced Research Projects Agency and performed under the direction of the U.S. Army Electronics Command as part of the Southeast Asia Communications Research (SEACORE) Program. The overall aim was to help overcome severe radio communications problems occurring in Southeast Asia. The present paper deals with one aspect of these investigations, namely, the measurement and analysis of path loss data. This path loss information was

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\* Only selected portions of the presentation are contained in this paper. A complete development of the presentation material is contained in the references.

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obtained by Jansky and Bailey (1,2) (A division of Atlantic Research Corporation), one of the prime contractors engaged in the SEACORE Program, and involved making extensive measurements at various locations in Thailand. The path loss measurements covered the frequency range from 100 kHz to 1.0 GHz encompassing a wide range of antenna heights, locations and seasonal rainfall variations.

The aim of our presentation is twofold: First, we shall be concerned with spot check statistical analysis of the information in the frequency range 2-400 MHz the results of which are then compared with previous results. Secondly, we shall set forth recommendations for further defining the statistical character of propagation loss data consistent with the original objectives of the SEACORE Project.

A realistic presentation of the analysis of the propagation loss data from a statistical point of view will be given in Section 2. In addition, we compare our spot check statistical analysis of the path loss information with previous results.

In Section 3, we shall present a summary of our preliminary findings, including recommendations for further analysis.

## 2. Stochastic Characterization of Path Loss Data

One of the major and most important points in the analysis of the SEACORE data is the manner in which one attempts to normalize the propagation loss to a common distance. The information collected by J&B was logarithmically transformed prior to their normalizing the data to a common distance. This transformed data was obtained by ECOM and analyzed with some of the results set forth in this paper. It should be recognized, however, that a fundamental question which must be considered is the extent to which this transformation altered the statistics of the data. Time did not permit this question to be fully considered but is presently being examined in some detail.

In our preliminary analysis, for specific configurations of frequency, transmitter antenna height, receiver antenna height, polarization, distance, and wet and dry classifications, i.e. (f, T, R, P, d, c), we obtained an estimate of the path loss distance dependency,  $\alpha$ , in such a way that the variance associated with the estimate will be minimum (i.e. maximum likelihood estimate) (3). We made spot checks of the  $\alpha$ 's corresponding to a particular set of experiments (i.e. radial A) to determine the best estimate for the following frequencies: 2, 6, 12, 25.5, 50, 100, 250\*, and 400\* MHz and for various combinations of transmitter and receiver antenna heights at distances of .2-2.0 miles. The data were classified as wet or dry by two criteria:

- (i) rainfall greater or less than 3 inches per month.
- (ii) rainfall greater or less than 6 inches per month.

\* The samples containing the measurements for 250 MHz and 400 MHz may be somewhat biased, (1).

TABLE 1a: SUMMARY OF PATH LOSS DISTANCE DEPENDENCY, ALPHA 1 FOR RADIAL A\* - VERTICAL POLARIZATION  
FOR 3" - 6" RAINFALL CRITERIA\*\*

FREQ (MHz)	T (Ft.)	R (Ft.)	DISTANCE (MI.)	ALPHA 1***	
				WET	DRY
25.5	40	20	0.2-2.0	37.9	31.4
		42		30.9	31.6
		79		31.4	33.6
50	40	20	0.2-2.0	23.7	21.5
		42		33.0	28.5
		79		32.0	29.7
100	40	20	0.2-2.0	49.4	32.5
		42		50.9	31.1
		79		43.1	31.7
250	40	20	0.2-2.0	16.0	27.5
		42		34.4	23.5
		79		38.4	28.5
400	40	20	0.2-2.0	31.2	21.2
		42		14.2	15.0
		79		36.0	34.4

\* Radial B data was not examined.

\*\* The results for the 3" and 6" rainfall criteria were the same. The 3" & 6" refer to the amount of monthly rain.

\*\*\* To achieve the proper distance dependency, the data was referenced to a common distance, which for our purposes was chosen to be 0.2 mile.

TABLE 10. SUMMARY OF PATH LOSS DISTANCE DEPENDENCY, ALPHA 1 FOR RADIAL A\* - HORIZONTAL POLARIZATION  
FOR THE 3" - 6" RAINFALL CRITERIA\*\*

FREQ (MHz)	T (Ft)	R (Ft)	DISTANCE (MI)	ALPHA***	
				WET	DRY
2	40	23 45 76	0.2-2.0	39.0 38.0 38.0	41.5 40.1 40.3
6	40	23 45 76	0.2-2.0	42.7 42.5 42.4	42.9 39.1 40.2
12	40	23 45 76	0.2-2.0	32.1 33.3 32.4	38.7 39.3 33.9
25.5	40	20 42 79	0.2-2.0	33.5 37.0 31.4	30.6 29.7 31.9
50	40	20 42 79	0.2-2.0	38.6 45.2 39.9	37.0 41.5 35.3
100	40	20 42 79	0.2-2.0	40.2 35.1 38.3	39.3 31.7 34.3
250	40	20 42 79	0.2-2.0	28.3 15.9 21.8	27.8 17.6 32.5
400	40	20 42 79	0.2-2.0	23.4 13.3 36.3	31.2 33.3 44.7

\* Radial B was not examined.

\*\* The results for the 3" and 6" rainfall criteria were the same. The 3" & 6" refer to the amount of monthly rain.

\*\*\* To achieve the proper distance dependency, the data was referenced to a common distance, which for our purposes was chosen to be 0.2 mile.

TABLE II: MINIMUM VALUE, MEAN VALUE, MAXIMUM VALUE, AND STANDARD DEVIATION OF ALPHA 1 FOR WET, DRY, AND WET PLUS DRY CONDITIONS WITH 3" - 5" RAINFALL CRITERION\*, HORIZONTAL POLARIZATION

FREQ (MHz)	SEA	MINIMUM ALPHA 1	MEAN ALPHA 1	MAXIMUM ALPHA 1	STANDARD DEVIATION ALPHA 1
2-400	Wet	13.3	34.8	52.5	+ 9.0
2-400	Dry	17.6	35.7	44.7	+ 6.0
2-400	Wet + Dry	13.3	35.3	52.5	+ 7.6
2-100	Wet + Dry	29.7	37.9	52.5	+ 4.6
250-400	Wet + Dry	43.3	27.2	44.7	+ 9.2

\* The results for the 3 inch and 6 inch criteria were the same.

The calculated best estimates,  $\hat{\alpha}_1$ , for the selected configurations are given in Tables Ia, and Ib.

We have found that for specific configurations of the parameters involved, there is a fluctuation from 13 to 52.5 dB. It is clear from Tables Ia and Ib that the estimates,  $\hat{\alpha}_1$ , behave as a random variable. These preliminary findings indicate that the media should definitely not be considered as a deterministic phenomena and that deterministic presentation of the data would give misleading results with respect to further characterization of the propagation loss as a function of the various independent parameters. When one utilizes a deterministic formula one can not help but force the data to accept the theoretical behavior of a deterministic phenomena. That is, the resulting conclusions are forced to be consistent to those which the deterministic theory dictates.

Results shown in Table II reveal a mean  $\bar{\alpha}_1$ , of 35.7 dB for the dry classification with a standard error of 6 dB, and for the wet classification a sample mean of 34.8 dB with a standard error of 9.0 dB. These values of standard error indicate that the respective averages for dry and wet classifications are not adequate. Furthermore, if we combine the wet and dry data, (the feasibility of combining the data is discussed in (3)) we obtain a sample mean  $\bar{\alpha}_1$ , of 35.3 dB, and a standard deviation of approximately 7.6 dB. This simply indicates that if we are allowed to combine the wet and dry propagation losses, that is, if there is no significant difference between the two data sets, we should be utilizing approximately 35 dB (as a rough estimate of  $\alpha_1$ ) to normalize the data with respect to distance. Since previous investigations employing a deterministic formulation (4,5,6,7) have shown that the distance dependency of the path loss varies as  $40 \log d$  in the frequency range 2-200 MHz, the data was separated into two sets and examined; namely, 2-100 MHz and 250-400 MHz. Table II shows  $\bar{\alpha}_1 = 37.9$  dB with a standard error = 4.6 dB for the 2-100 MHz range and  $\bar{\alpha}_1 = 27.2$  dB with a standard error = 9.2 dB for the 250-400 MHz range. This indicates that the deterministic  $40 \log d$  more closely fits the 2-100 MHz range. In view of the above remarks one should consider the following equation for normalizing the propagation losses referenced to a common distance:

$$Z_i = X_i - \hat{\alpha}_1 \log(d_i), \quad i = 1, 2, \dots, n$$

where  $Z_i$  is the normalized path loss data and  $X_i$  is the measured path loss data.

Other statistical quantities have been calculated (i.e. confidence bounds, null hypothesis testing of wet vs dry, expected value of the wave via Maxwell's curl equations, etc.) and are reported elsewhere (3, 8).

### 3. Summary and Recommendations.

We have obtained enough information from the statistical analysis of the SEACORE data reported here and elsewhere (3) to make the following conclusions:

(1) It is evident that the data should be given a more sophisticated statistical analysis for firm decisions on the various questions raised with respect to behavior of the propagation loss as a function of the various independent variables (i.e., antenna heights, polarization, frequency, distance).

(2) We have obtained enough evidence to show a deterministic approach used to normalize the data to a common distance is not acceptable to relate the propagation loss to a common distance.

(3) A statistical approach to estimating an  $\alpha$  so as to minimize the variance of this estimate, using the logarithmic data, has been presented and evaluated for specific parameter configurations of the SEACORE data. It is clear that in normalizing the path loss data, using this technique, significantly different results are obtained which effect the statistical decisions one needs to make with respect to the behavior of propagation loss in a jungle environment.

(4) To adequately answer the original objectives of the SEACORE Program, the importance of the path loss data presented in the reports by J&B cannot be overlooked. Our preliminary investigations employing statistical techniques have answered a number of questions and indicate the importance of a thorough statistical analysis of the propagation loss data. It should also be mentioned that there is very little work, if any, which has been done in the subject area from a sophisticated statistical analysis approach. We feel that such an approach is much more realistic to the problem at hand than deterministic investigations, and the preliminary findings certainly justify this point of view.

(5) Based on our findings, the following guidance should be considered with respect to the complete statistical modeling of the SEACORE path loss data:

(a) In the statistical analysis of the SEACORE data a very basic question must be answered. That is, should one perform the statistical analysis on the data in dB, (i.e. having it logarithmically transformed) or should the anti-log data be used?

(b) A thorough classification of the data with respect to wet-dry conditions should be made. The problem of propagation loss should be investigated under three classification categories:

- (i) daily basis (if present data permits),
- (ii) monthly basis,
- (iii) seasonal basis.

Furthermore, the effect of path differences should be determined if possible.

c. Having chosen the proper method for normalizing propagation loss to a common distance we need to develop a super alpha, i.e.,  $\alpha'$ , for specific sets of parameter configurations, that will provide a realistic technique

which can be used to predict path loss as a function of distance. Since there is a significant difference among the  $\alpha$ 's measured for each parameter configuration, one should not treat the estimate of the  $\alpha$ 's as a deterministic parameter but rather as a random variable. To this effect we need to formulate statistical techniques through the empirical Bayes approach, i.e., to group these  $\alpha$ 's into a common one. For a certain group of frequencies, transmitter and receiver antenna height, and polarization, we should have a statistical estimate of an  $\alpha$ ' which is made up of a group of  $\alpha$ 's which can be easily applied to a physical situation for communication design purposes.

(d) Having path loss as the main variable, we need to classify the contributing variables, that is, independent variables such as transmitter antenna height, receiver antenna height, distance, polarization and frequency, according to their importance as contributing factors. This investigation can be done through multiple correlation analysis. Its importance lies in the fact that if a certain independent variable, such as changing the antenna height, does not contribute significantly to a change in propagation loss, then we should not consider it as one of the important variables in the statistical modeling. In other words, we should be concentrating on the independent variables which contribute most to the dependent variables. Such a classification of the independent random variables will be extremely helpful in accomplishing the succeeding recommendations.

(e) Having classified the importance of the random variables as contributing factors to the propagation loss, it is recommended that a non-linear regression model be developed. Once a non-linear regression model has been formulated, with path loss as the main objective, which is a function of transmitter antenna height, receiver antenna height, distance, polarization, and frequency, one can specify an acceptable propagation loss and obtain the proper combinations of the independent variables required to attain this loss. An important factor in this recommendation is that if you are not willing to accept more than, say, 150 dB for path loss at a specific frequency and distance, what combination of antenna heights will not violate the proposed specification. One can proceed in formulating such a non-linear regression model through an elimination procedure, that is, consider a model which will consist, first, of the dependent variable being a function of the antenna heights. Thus, with a specific frequency and distance, the possible combinations of antenna height will be determined so that we can maintain a specified propagation loss. Secondly, with this approach one can increase the size of the model by having the dependent variable as a function of the antenna heights and distance.

(f) In our preliminary investigation of the SEACORE data, our statistical analysis was restricted primarily to distances between .2-2.0 miles. It is also recommended that the above recommendations be considered for longer distances, that is, 2.0 - 15.0 miles.

(g) For selected sets of the control variables, taking into consideration the above decisions, confidence intervals should be obtained for the mean path loss (true state of nature) on the basis of the experimental evidence.

In summary, the preliminary findings of our statistical analysis are quite evident, and as a result, the above recommendations constitute some of the essential elements for the final aspects of the SEACORE Project. The value of this data, which has been collected at a great cost to the U.S. Government, should be fully utilized to attain the answers to the questions posed above. The results of sophisticated analysis will make significant contributions in aiding communications engineers to determine transmission reliability and, ultimately, better communications.

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PANAMA CANAL ZONE JUNGLE PREDICTIONS  
AND MEASUREMENTS AT 49.4 AND 160.1 MHz

by

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PANAMA CANAL ZONE JUNGLE PREDICTIONS  
AND MEASUREMENTS AT 49.4 AND 160.1 MHz

In order to determine the extent to which path loss predictions based on computerized models can be relied upon for communication planning in jungle terrain, path loss measurements were made at 49.4 and 160.1 MHz using man-pack receivers in the Panama Canal Zone in October 1969. A transmitting site on a hill surrounded by jungle terrain was selected. For that site area predictions were generated from two computer models developed separately by the Electromagnetic Compatibility Analysis Center (ECAC) and the General Research Corporation (GRC). Since only the GRC model included the effects of trees, direct comparison of models was not possible. There were significant differences (30 db) between the GRC predicted results and measured values of path loss at 49 MHz. Since the GRC model had been shown to be accurate when calculations were compared with values measured by Jansky and Bailey (J&B) in Thailand, reasons for the differences were investigated and corrections made to the model to obtain a reasonable match between the calculated and the measured values. The conclusions were reached by the author that additional comparison of measured and calculated results should be made before the model can be considered totally developed.

Measurement Technique

The AN/PRC-25 was used for the 49.4 MHz measurements, and the Motorola PT-400 for the 160.1 MHz measurements. Both have a tone-operated squelch, characterized by a stable threshold. The received signal strength was measured relative to this threshold by inserting a calibrated variable attenuator between the antenna and the receiver to reduce the received signal to the threshold value. Path loss up to 172 db could be measured with this technique.

Measurement Location

The test area was located at the U. S. Army Tropical Test Center, Fort Clayton, P. O. Z. The transmitters were located at a base camp

at abandoned hilltop radar site. Measurements at 49.4 MHz, vertical polarization were made at 68 points (at 160.1 MHz, only 23 points) at ranges from 9 to 42 km.

### Analysis of Data

Two criteria were used to evaluate the data:

(1) The statistical characteristics of the difference,  $D$ , between measured ( $x$ ) and predicted ( $y$ ) results, and,

(2) The statistical characteristics of the linear regression,  $y = b_0 + b_1x$ , obtained by plotting the predicted ( $y$ ) vs. the measured ( $x$ ) results.

$$1. (a) \quad \bar{D} = \frac{\sum (X-Y)}{n} \quad \text{BEST ESTIMATE OF MEAN DIFFERENCE}$$

$$(b) \quad s = \sqrt{\frac{n \sum (X-Y)^2 - \{\sum (X-Y)\}^2}{n(n-1)}} \quad \text{BEST ESTIMATE OF } \sigma$$

$$(c) \quad D_{U_L} = \bar{D} \pm t_{.975} \frac{s}{\sqrt{n}} \quad \text{95\% CONFIDENCE LIMITS}$$

$$(d) \quad S_{U_L} = R_{U_L} S \quad \text{95\% CONFIDENCE LIMITS}$$

2. (a)  $Y = b_0 + b_1 X$  LINEAR EQUATION

(b)  $b_0 = \bar{Y} - b_1 \bar{X}$  Y INTERCEPT

(c)  $b_1 = \frac{\sum (X - \bar{X})(Y - \bar{Y})}{\sum (X - \bar{X})^2}$  SLOPE

(d)  $r = \frac{\sum (X - \bar{X})(Y - \bar{Y})}{\sqrt{\sum (X - \bar{X})^2 \sum (Y - \bar{Y})^2}}$  CORRELATION COEFFICIENT

(e)  $s_{b_1}^2 = \frac{S_y^2}{S_{XX}}$  ESTIMATED STANDARD DEVIATION OF SLOPE

Criteria for goodness of fit are

- (1) minimum  $\bar{D}$
- (2) minimum  $s$
- (3) minimum  $b_0$
- (4)  $b_1$  near unity
- (5) maximum correlation coefficient
- (6) minimum  $s_{b_1}$

The upper and lower values of  $\bar{D}$ ,  $s$  and  $s_{b1}$  permit comparison when  $n$ , the number of samples, are not equal.

Measurements were made at 68 points at 49.9 MHz and these were compared with levels taken from an area prediction overlay. The results are tabulated in Table 1.

TABLE 1 - 49.4 MHz INITIAL COMPARISON - AREA PREDICTION

	n	$\bar{D}^U$ db L	$s^U$ db L	$b_o$ db	$s_{b1}^U$ L	r
Y (h=70)	68	-25.5	18.7		.45	
		-29.3	15.6	122.9	.29	.40
		-33.0	13.2		.12	
X (no trees)	63	24.4	22.0		.68	
		19.8	18.2	55.5	.42	.38
		15.2	15.4		.16	

As seen the GRC prediction was 29.3 db too high; the ECAC 19.8 db too low (due to lack of trees in the model). The correlation coefficient,  $r$ , is low. Comparison of the standard deviation,  $s$ , shows the GRC model to have the lower value.

Had the results of the work shown better comparison between the measured and predicted values, the task would have been successfully completed in showing that area predictions could be used. Since this was not the case, point-to-point calculations were made, corresponding to the points where measurements were taken. It is estimated that the points were located to within 100 meters on the map. Comparison results are shown in Table 2.

TABLE 2 - 49.4 MHz INITIAL COMPARISON - POINT TO POINT

	n	$\bar{D}^U$ db L	$s^U$ db L	$b_o$ db	$s_{b1}^U$ L	r
Y (no trees)	68	-7.3	16.7		.43	
		-10.7	14.0	162.2	.30	.50
		-14.1	11.9		.17	
X (no trees)	67	25.4	16.5		1.07	
		22.1	13.7	-4.2	.86	.72
		18.7	11.7		.66	

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The point-to-point ECAC prediction (compared to comparable GRC results) have the higher correlation coefficient, lower, standard deviation, and a slope nearer unity. A calculation of path loss at calibration point 30 (102.9 db) compared well with the measured value (103.8 db). The GRC predicted result (132.1 db) was in error because the effective height of the transmitting antenna was calculated to be 6 meters, too low compared to the actual height of 219 meters. This was due to faulty Fresnel Zone clearance criteria. This was corrected and new predictions made.

GRC predictions were made for tree heights of 70', 60', 50', and for index of refractive value of  $1.4/3 \infty$ . Comparison of results showed that the attenuation did not decrease with tree height at each point as was to be expected. The model was re-examined, an error found and the model was corrected.

At the same time, it was observed that the behavior of the prediction with varying index of refraction was excessive at some point--here again, errors in the model were found and again corrected. The results are shown in Table 3 (n=58);

TABLE 3 - 49.4 MHz CORRECTED MODEL -Y

	n	$\bar{D}_{db}$	$S_{db}$	$b_{odb}$	$b_1$	r
Y (h=70')	68	2.13	11.6	54.9	.57	.70
Y (h=70')	67	2.68	10.8	52.0	.58	.74
Y (h=70' L.O.S.)	25	-3.2	7	17.8	.88	.75
Y (h=70', 1 obstacle)	18	7.0	8.6	77.5	.30	.48
Y (h=70', 2 obstacles)	24	5.3	12.8	79.3	.40	.56

The prediction for point 47 was the only one left which indicated a fault due (to a variation of 30.4 db for  $1 < k < \infty$ ). This point was therefore considered invalid. The standard deviation, s, of 10.8 db,  $\bar{D}$  of 2.68 db and correlation coefficient, n, of .74 was considered acceptable for the remaining 67 points.

Of the 67 valid GRC predictions, 25 were line-of-sight, 18 had one obstacle, 24 had two or more obstacles. The results for these breakdowns are also shown in Table 3. Also of the 67 points, 56 were measured in jungle. A breakdown of results for all jungle points is given in Table 4. Indications of how to improve the GRC model can be obtained by studying these data. For example, the mean predicted attenuation for one-obstacle paths is too low by about 7 db. The standard deviation,  $s$ , for the two-or more obstacle paths is about 4 db higher than the one-obstacle paths and 6 db higher than the line-of-sight paths.

TABLE 4 - 49.4 MHz CORRECTED MODEL - Y - JUNGLE POINTS

	n	$\bar{D}_{db}$	$S_{db}$	$b_{db}$	$b_1$	r
$Y_j$ (h=70')	56	2.54	11.0	65.7	.49	.68
	(67)	2.68	11.6	54.9	.58	.74)
$Y_j$ (LOS)	20	-2.8	7.6	20.5	.85	.62
$Y_j$ (1 obstacle)	15	6.7	9.2	62.6	.49	.56
$Y_j$ (2 obstacles)	21	4.6	13.1	111.2	.20	.44

The results measured at 160.1 MHz are compared with the predictions using the model as improved. The mean difference is 16.2 db indicating the need to further improve the model. By changing the equivalent dielectric constant of the jungle model from 1.05 to 1.07 the mean difference is changed by 18.2 db to -2.0 db. The results at 49.4 MHz change the mean difference by 5.7 db to 2.6 db. (See Table 5).

TABLE 5 - 160.1 MHz CORRECTED MODEL - Y

	n	$D_L^U$ db	$S_L^U$ db	$b_o$ db	$b_{1L}^U$	r
Y (h=70')	23	21.4	16.8		1.89	
$c=1.05$		16.2	12.1	-18.8	1.26	.67
		11.0	9.2		.63	
Y (h=70')	23	-2.0	15.0			
$c=1.01$						
Y (h=70')	68	-2.6	11.8			
f49.4 $c=1.01$						

A comparison was made between the GRC and ECAC models which utilized the same terrain data. The mean difference (-GRC +ECAC) was 5.5 db and the standard deviation was 14.5 db which is worse than the correlation with the measured results.

It is concluded that there is a need to further improve the models used. The analysis done indicated that improvement can be made by (1) comparing the two models and incorporating the best parts of each into the final model and (2) comparing results with predicted values to bring the two in closer agreement. One should be able to predict the mean difference to an accuracy of  $\pm 2$  db with a standard deviation of 8 or 9 db.

By using the squeich threshold as a reference for path loss measurement, the path loss using a PRC 25 was measured up to 172 db ( $\pm 1$  db). Also by using a prototype village alarm system developed by RCA under ARPA sponsorship, it was found that path loss up to 186 db could be measured. At no time did the system give a false alarm.

Thus, it was demonstrated that the alarm system would work reliably as long as the path loss was less than 186 db. In Panama, at ranges up to 42 km, the measured path loss was never greater than 172 db at 49.4 MHz.

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THEORY OF  
RADIO PROPAGATION IN A JUNGLE ENVIRONMENT

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## Section 1

### INTRODUCTION

The objective of this theoretical effort was to devise simple models representing propagation in a jungle environment which could be implemented in a digital simulation and yield accurate results with a minimum of computational time. The simplest model satisfying these requirements is the conducting dielectric slab over a flat earth. This slab model was shown to agree with experimental measurements in a Thailand jungle within a standard deviation of 6 dB for the frequency range 6-100 MHz.

This report is in two parts. The first part describes the basic smooth-earth slab model and the computer subroutines which calculate radio-path loss for various situations. Each situation allows different approximations which simplify the calculations. The second part describes a model and several computer subroutines for the calculation of the effects of terrain irregularities and jungle discontinuities on path loss. This model is a combination of the slab model of the jungle and the knife-edge model for the case of ridge diffraction.

Where data is available, comparisons are made with experimental measurements taken in a Thailand jungle.

The end product of this work is a set of computer subroutines which give basic radio-path loss for many possible configurations of antennas in many types of terrain. These routines consider the

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electric field radiated by an elementary dipole whose strength (current x length) is such that it would have radiated P kilowatts in free space. The actual output of these routines, however, is "basic path loss"

$$L_b = L_{bf} + 20 \log \left( \frac{E_{\text{free space}}}{E_{\text{environment}}} \right) \text{ constant dipole moment}$$

The first term on the right side,  $L_{bf}$ , is the basic path loss in free space, defined by Norton as the ratio (in dB) of the power radiated by an isotropic lossless transmitting antenna in free space to that available to an isotropic lossless receiving antenna in free space.

Each calculated value of electric field is transformed into basic path loss by the equation

$$L_b = 19.0 - 20 \log E + 20 \log f$$

where  $f$  is the frequency in megahertz, and  $E$  is the RMS electric field in the actual environment in volts per meter, calculated as if it were received from a point dipole which would radiate one kilowatt if situated in free space.

## Section 2

### CONTINUOUS TERRAIN - THE SLAB MODEL

An approximation to the jungle is considered, which consists of a uniform slab of fixed height bounded below by a flat-earth surface and above by the air with vacuum properties. The transmitting and receiving antennas may be either above or within the jungle.

The mathematical problem of obtaining the electric field at the position of the receiving antenna, produced by a point dipole at the position of the transmitting antenna, has already been extensively studied for a many-layered medium, and admits an exact solution in an integral form.

#### ANTENNAS WITHIN, OR SLIGHTLY ABOVE, THE JUNGLE

For this situation, the dominant direction of propagation is horizontal. The following method of integral evaluation uses that fact to best advantage.

The integrand vanishes on an infinite semicircle in the upper half plane. The original contour which lay along the real axis is therefore deformed to this semicircle. One is left with integrals along two branch cuts and contributions from poles that were crossed.

The poles correspond to transmission modes through the jungle that are exponentially damped. One cut corresponds to a

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wave propagating laterally along the jungle-ground boundary. This wave is highly attenuated because of the high conductivity of the ground and is negligible compared to other contributions to the resultant field. The other cut corresponds to a lateral wave along the jungle-air boundary. This wave is not exponentially attenuated and is therefore the dominant contribution after one damping length of the pole terms.

When both antennas are below the jungle top, this cut contribution is properly called the lateral wave. The term "lateral" arises since the radiation does not simply reflect from the jungle-air interface, but rather enters the interface from the transmitter, suffers a long lateral displacement, and returns from the interface to the receiver. If one antenna is above the jungle, the cut now corresponds to the ray that travels from one medium to another obeying Snell's law. This ray propagates horizontally through the air and enters the jungle at the complex critical angle. If both of the antennas are above the jungle, the cut corresponds to a combination of a space wave and the usual "surface" wave of radio propagation, except in this case the surface is jungle over ground rather than bare ground. Thus, it can be seen that the one cut which corresponds to varied interpretations depending on the location of the antennas, is really one mode of propagation through the air, which is a familiar mode if the antennas are above the jungle.

If either antenna is higher than a Fresnel zone above the jungle, the poles lose their physical meaning as waveguide modes and are no longer negligible, thereby nullifying the usefulness of the above procedure. This case is treated separately in the section on one high antenna.

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We have obtained an integral representation of the lateral wave valid for ranges greater than a wavelength. This integral is evaluated numerically in a computer routine called JUNGLB.

#### LOW-FREQUENCY VERTICAL POLARIZATION

For the case of vertical polarization only, JUNGLB must be supplemented by another computer routine at low frequencies and ranges. This routine (called LOVE) is a combination of a low-frequency solution for ground wave propagation due to Sommerfeld (and others) and its extension to a two-layered medium due to Wait.

#### ONE HIGH ANTENNA

For the situation where one antenna is too high above the vegetation for JUNGLB to be accurate, the previously defined method of treating the original integral is abandoned, and the integral is evaluated along a steepest-descent path corresponding to a ray propagating to or from the high antenna, rather than along the ground interface. The value of  $E$  used is the RMS value of the total electric field vector which is perpendicular to the ray direction at high altitude. A factor of  $\sin \theta$  has been omitted so that the basic path loss derived from  $E$  will correspond to an isotropic radiating antenna. The routine which evaluates the field in this manner is called HI.

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### Section 3

#### DISCONTINUOUS TERRAIN — THE DIFFRACTION MODEL

The problem of propagation over two dissimilar paths and the problem of diffraction over an obstacle are handled by the same basic method, a combination of Green's theorem and the Kirchhoff approximation. This method is the same as that used to obtain the solution in the problem of Fresnel diffraction by a straight edge. Green's theorem makes it possible to obtain the signal at any point to the right of a plane in terms of the value of the signal on that plane. The Kirchhoff approximation is the assumption that the signal on the plane below the limit of the obstacle (the ridge top or the jungle top if no ridge is present) is zero, and the signal above the obstacle is that which would occur if the medium on the left of the plane also existed continuously on the right, i.e., the ridge is absent and the media on both sides of the plane are identical.

This procedure leads in all cases to an integral over the plane of the product of two functions which represent, respectively, the signal on the plane due to the transmitter and the signal on the plane due to the receiver (as if it were transmitting). It is therefore necessary to have analytic expressions for these signals so that one does not have to integrate over the results of other numerical integrations.

We have built four different computer subroutines which treat four separate situations:

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1. **MIXLB** — a numerical routine which treats the case of antennas within or slightly above a jungle where the character of the jungle and ground is different in the vicinity of each antenna. This admits the possibility of no jungle at all at one or both antenna locations. This routine, which is the most accurate and time-consuming of the four, includes the case where the boundary between the media can be very close to one of the antennas. Such a situation is not allowed by the other three routines.
2. **HAFAS** — a simple, short and approximate routine which treats the case of one antenna in or slightly above jungle, and the other antenna far from any reflecting boundaries so that the signal from that antenna to the plane is a free-space signal.
3. **MXLDIF** — a comprehensive routine which treats the cases of antennas of any height, in media of any type, and elevation separated by a single obstacle of any height.
4. **TWOPIK** — an extension of **MXLDIF** which treats the case of two obstacles separated by media of any type and any elevation below the lowest obstacle. This routine is not as accurate as **MXLDIF**, since it includes an additional assumption regarding two-ridge diffraction which breaks down for cases of small diffraction loss. The additional computation time necessary to make it as accurate as **MXLDIF** is unwarranted, since the expected diffraction loss for the cases where it breaks down is less than 6 dB. The routine, therefore, is simply not called in those cases where the heights of both obstacles are small enough so that the expected diffraction loss is less than 6 dB.

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## Section 4

### COMPARISON WITH EXPERIMENT

#### LOW-FREQUENCY VERTICAL POLARIZATION

Path-loss predictions using the slab model of the jungle have been shown to agree with experimental measurements in a Thailand jungle without a standard deviation of 6 dB for the frequency range 6-100 MHz. Predictions at frequencies above 100 MHz were shown to be in less agreement. For frequencies below 6 MHz, the data showed the path loss to be close to that which would be predicted by classical smooth-earth procedures. Closer examination of this measurement data, however, has shown that an assumption of bare ground is not strictly valid and that better path loss predictions are possible. A routine incorporating jungle effects has been evolved for low-frequency vertical polarization cases and designated LOVE.

A comparison of data with calculations from LOVE has been made, wherein the calculations employed the jungle and ground constants which were previously chosen as best for the 6-100 MHz comparisons. The agreement is excellent.

#### OBSTRUCTIONS

The original comparisons of the continuous terrain model (JUNGLB) with the experimental data taken by Jansky and Bailey were made for ranges of one mile or less, since there were intervening hills for all range points beyond a mile. Subsequently, comparisons

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with their data were made for ranges beyond a mile, using predictions from the obstacle routines MXLDIF and TWOPIK. The range of frequencies considered was 6 to 400 MHz. The jungle and ground constants used were similar to those used previously for best fit in the original comparisons for smaller ranges.

The overall comparisons for the many range points, antenna heights, and frequency show a near zero mean difference with a standard deviation of about 5 dB.

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APPLICATIONS OF RADIO PROPAGATION MODELS

by

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## APPLICATIONS OF RADIO PROPAGATION MODELS

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### BACKGROUND

From 1965 to 1968, General Research Corporation engaged in a study for the Advanced Research Projects Agency concerning the problem of analyzing the tactical communications of lower level military units operating in jungle-covered terrain. This activity was conducted simultaneously and in cooperation with other ARPA and SEACORE contractors.

The study objective was to produce a means for rapidly assessing, with some known degree of confidence, just how well any given radio communication system would perform (from both the technical communication system standpoint and from the tactical usefulness standpoint) in dynamic tactical operations such as were being conducted in Viet Nam.

The method chosen to implement this objective was a simulation which would model:

- realistic military unit deployments (including unit movements), each unit using appropriate tactical radio equipment in all appropriate nets
- good path loss calculations for each link in each net, taking into account the actual vegetation and terrain features which affect the various propagation paths as units move about in the area of operations
- tactical message traffic typical of such operations, each message specifically related to the tactical operation in terms of content, originator, addressee, precedence, and time of origination.

A simulation, embodying these characteristics, was constructed and was designated TACOS II. It was used in its entirety or in part, to assess a number of different communication problems. The remainder of this paper presents a brief description of the simulation and some examples of its use.

### SIMULATION DESCRIPTION

Three basic types of models are used in combination to simulate tactical communication operations: (1) a tactical model to generate the positions and message requirements of combat units engaged in field operations; (2) a link status model to ascertain the operability of each communication link in a system as a function of time and the location of its terminals (combat units) in the simulated environment; and (3) a message processing model to determine the actual time sequence of the stages each message goes through from the time it is first filed until it is successfully completed. Figure 1 shows a block diagram of the simulation.

### Tactical Models

The most sophisticated tactical model, INSURGE-II, is a computerized two-sided tactical engagement game that provides a dynamic environment for testing tactical

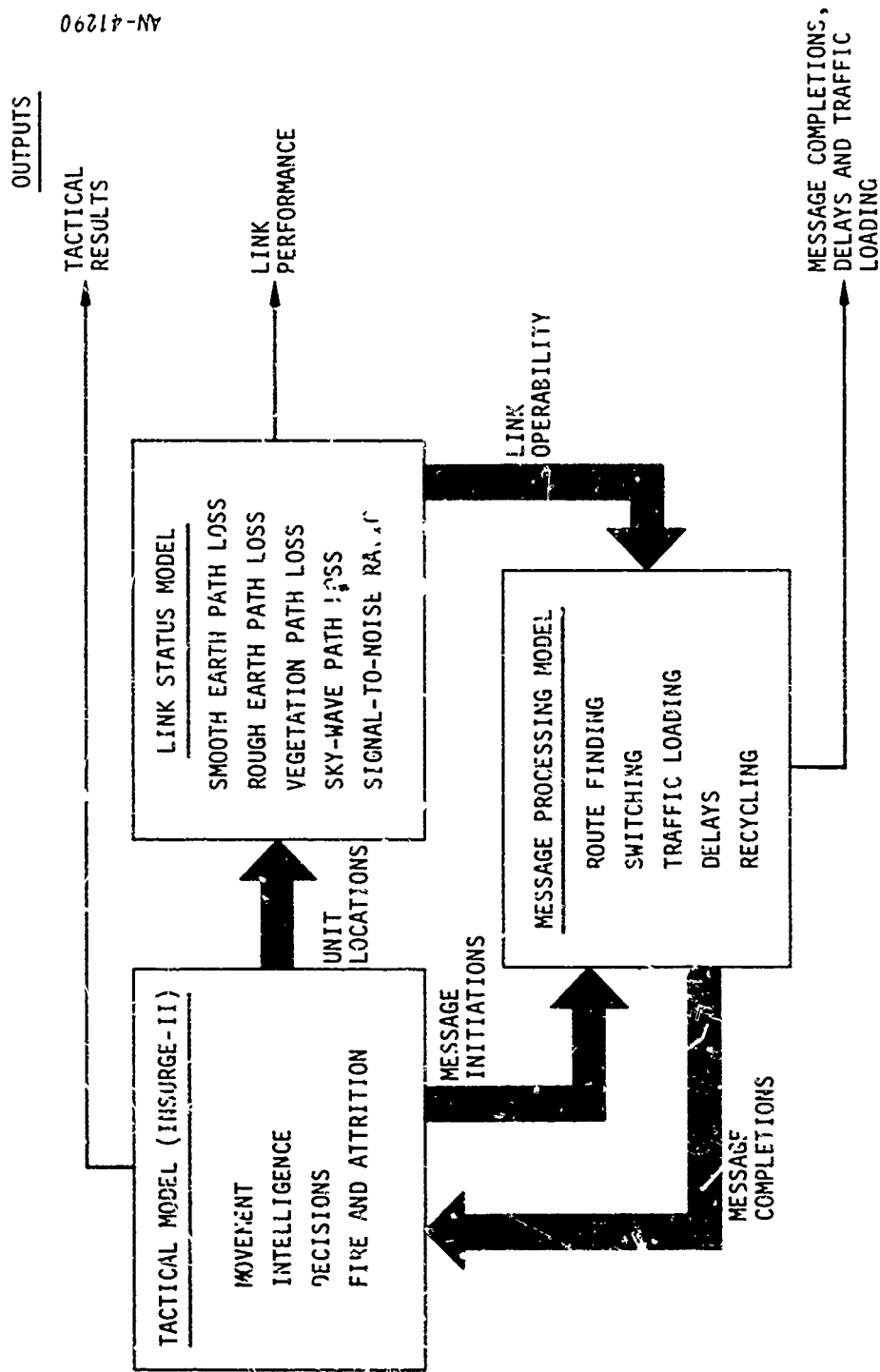


Figure 1. Block Diagram of TACOS-II Simulation

communication systems in the TACOS-II simulation. The model accomplishes this task by (1) moving combat units over terrain in a realistic tactical manner, (2) initiating specific requirements for tactical messages as a function of individual unit combat situations, and (3) reacting to the completion of tactical messages by using their information to influence subsequent tactical activities.

In the INSURGE-II tactical model, friendly and enemy forces are assigned strengths (number of troops), weapons, command structures, initial dispositions in the area of interest, and combat missions appropriate to their capabilities. The model simulates unit movement and the acquisition of intelligence, considering environment and enemy activity. Tactical decisions based on orders and acquired intelligence are made repetitively for each unit in accordance with its assigned mission.

Available artillery and air fire support is provided (with the approval of affected higher headquarters) based upon situation reports received from the requesting combat units. Fire between units in contact is modeled with weapon effectiveness governed by range and terrain considerations. Attrition resulting from these engagements and from supporting artillery, from heavy weapons, and from aircraft, is calculated, and unit strengths are correspondingly modified.

Several less sophisticated tactical models were also developed and can be used. The INSURGE-I tactical model has the same features as the INSURGE-II model except for the multi-level command and control exercised by headquarters units. It is useful for studying the actions of combat units which act independently of other friendly units. A third skeletal tactical model can also be employed to assess communication situations which are primarily static or when deployment changes are pre-determined. This model causes units to move and generate messages only in accord with pre-specified inputs.

#### Link Status Model

The link status model determines to what degree any given communication link is operable as a function of terminal equipment and the propagation path conditions existing between units at each end of the link. Propagation via ground wave or via near-vertical skywave paths is modeled.

The ground wave path loss procedures first determine the nature and structure of vegetation and terrain variations along the propagation path; the model then calculates path loss using the most appropriate of nine methods, eight of which are based upon the characterization of vegetation as a lossy dielectric slab (described elsewhere herein by Dr. David Sachs). The skywave elements of the model solve the Appleton-Hartree equation for the height of reflection in the ionosphere, described by its electron density and collision frequency profiles. The loss in the ionosphere is obtained by integration over the ray path.

The signal-to noise ratio (and hence the link operability) is calculated from input hardware characteristics, from median values of path loss and atmospheric or cosmic noise, and from probabilistic adjustments to such median values derived from input statistics regarding the uncertainty in their true value. Such probable variations in path loss and antenna pattern distortions due to jungle environments are based on measurement data taken by SEACURE contractors in Southeast Asia.

### Message Processing Model

This model must be operated in conjunction with one of the tactical models (which specify messages and their initiation times) and the link status model (which specifies link operability). Other input data describe the structure of the communication system, permissible routings for the various possible message types, rules governing the use of message precedence on system traffic handling, recycling procedures to be used when routes are busy, etc. Utilizing this information, the message processing model attempts to route each tactical message to its addressee respecting the technical status, the traffic conditions, and the operating practices of the modeled system. When no working route for a message is found, it is recycled after an appropriate delay.

In performing this function, the model necessarily produces information as to any delays encountered by each message and whether such delays are attributable to link outages or system traffic. It also records the specific route used to transmit each message.

### SIMULATION APPLICATIONS

#### Long Range Patrol Communication Equipment Requirements

About four years ago, ARPA undertook a program to systematically identify the unique attributes which small independent action forces (such as long range patrols operating in enemy-held territory) might generally require, and to recommend personnel selection and training methods and equipment requirements which might enhance the Armed Services' capability to field such units. Under this program General Research carried out a study project concerned with radio communications.

The essence of the study was to specify the performance required of radio sets which would allow satisfactory communication over the necessary ranges in three different environments: Southeast Asia, Middle East, and Europe. Performance of existing portable military radios was compared with that required, and necessary improvements defined in dB so that radio design engineers might judge the feasibility of obtaining such improvements by changes to transmitter power, antenna gains, transmission bandwidths, etc.

The results of the study were many and varied greatly depending on combinations of such factors as link type, environment, frequency, equipment characteristics, terminal station locations, etc.

Fundamental to this study was an assessment of values for maximum path loss which might be expected in the various environments at the maximum specified operating ranges. The most severe requirements were imposed by the need for a patrol to communicate directly with its parent unit (base station) by voice at a range of 100 km.

The link status model of the simulation was used to assess path loss values expected in three typical environments. Map data (topography and vegetation cover)

at 500 meter grid intervals was put into the computer. For Southeast Asia, an area near Pleiku, Viet Nam was used. For a substitute Middle East area, a portion of Nevada was used; for a substitute rugged European area, terrain near Fort Bragg was used.

In each mapped area, a number of reasonable base station sites, and potential patrol station sites deployed radially around the base station at various ranges, were selected and input to the link status model. Computations were then made for 228 cases using combinations of geographical areas, link terminal locations within each area, antenna heights above local terrain, frequencies, and polarizations.

A sample of the results of these computations is shown in Fig. 2 for one of the Pleiku base station locations where the base station and patrol antenna heights were 10 m and 2 m respectively, and the transmission frequency was 60 MHz, vertical polarization. Since the distributions of path loss at any given range were usually not normal, curves of the median path loss not exceeded in 10, 50, and 90% of the locations are shown.

These basic path loss estimates were evaluated and combined with variable path loss data to produce values of "maximum expected path loss" for the following link situations: Intrapatrol and patrol-to-patrol VHF links, Patrol-to-airborne platform VHF and UHF links, Patrol-to-base HF links, Patrol-to-base or mountaintop-relay VHF links.

Portable military radio sets now in use were evaluated, as appropriate, for their range performance in each communication-link situation. Figure 3 shows the dB improvement required above present VHF equipment (AN/PRC-25 or 77) capability to overcome losses sufficiently to provide 90% voice intelligibility at ranges of 50, 75, and 100 km in each geographical environment for three different deployment situations.

#### Hypothetical Multi-battalion Engagement

Following the development of the TACOS-II simulation, a family of test runs was made to check out model sensitivity to the random number processes used, and tactical outcome sensitivity to communication system performance and particular tactics employed.

Random number calculations are employed in all of the major models in TACOS-II. In the tactical model, probabilities are used to assess the detection and acquisition of intelligence by each combatant. In the message processing model, particular message origination times, lengths, and processing times are selected from distributions specified by input data. In the link status model, uncertainties in propagation path loss caused by fading, antenna pattern distortions, and imprecise descriptions of the environment are accounted for by adjustments to the basic loss calculations (considered as median values) which are drawn from distributions described by input data. These inputs, in turn, are based upon the variability experienced in field measurement programs. As a result, thousands of random numbers are employed in the probabilistic calculations performed during each run of the TACOS-II simulation. Hence, the outcome of one run is but a sample of a probability distribution, and a number of runs with identical inputs but different random number sequences are required to establish the nature of each distribution.

Upon completion of the development, a series of TACOS-II simulation runs were performed employing a single tactical setting. This battle involved a blue brigade-

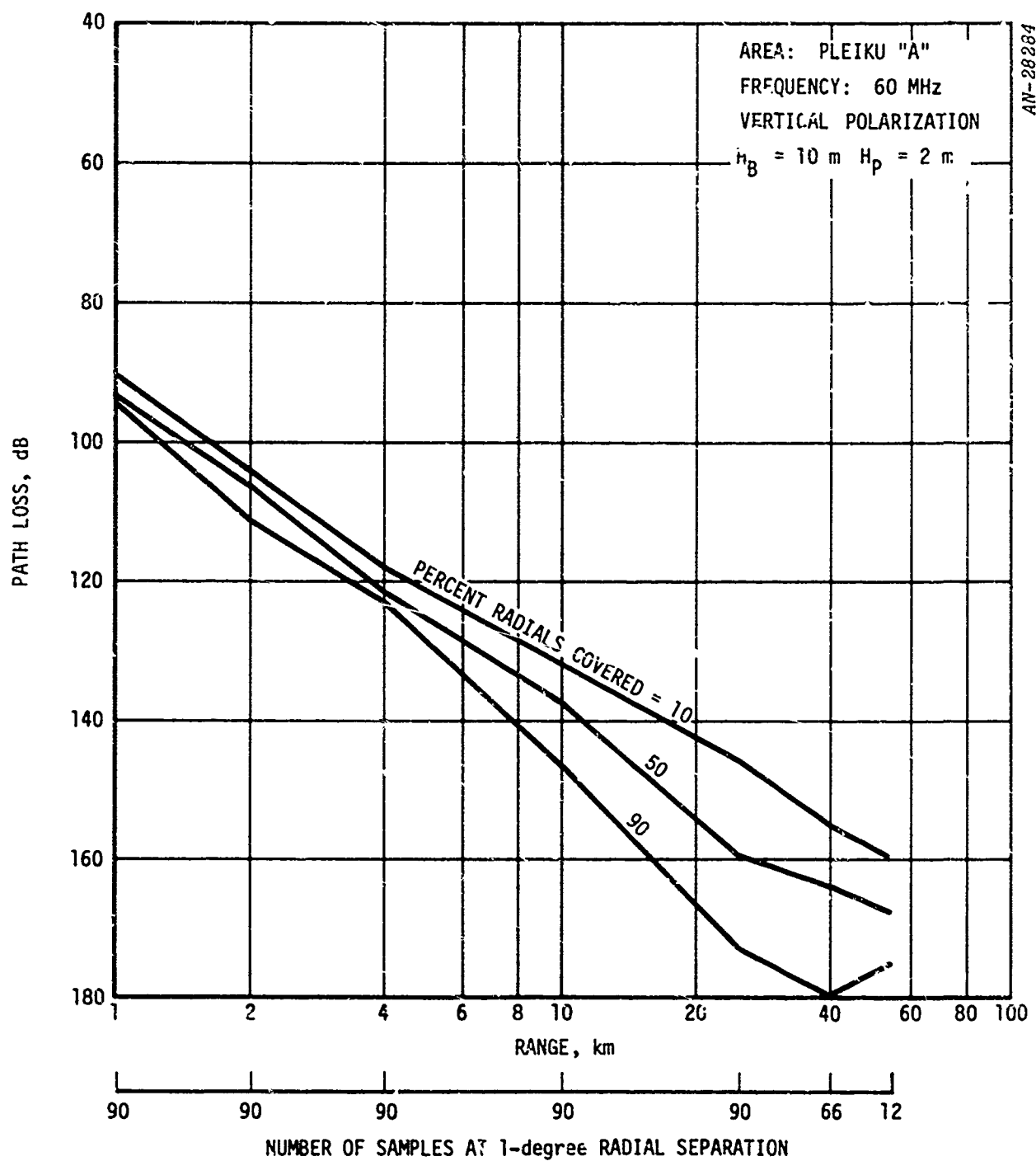


Figure 2.

I-I-6  
1043

FIG. 3 NEEDED dB IMPROVEMENT ABOVE PRESENT EQUIPMENT  
PERFORMANCE FOR PATROL-TO-ANY BASE STATION VHF RADIO LINKS

Vertical Polarization  
90% Voice Intelligibility

	Pleiku		North Carolina		Nevada	
	30 MHz	60 MHz	30 MHz	60 MHz	30 MHz	60 MHz
PATROL-TO-NONELEVATED BASE STATION RADIO LINKS						
100-km Range	53	47	43	35	26	20
75-km Range	44	37	33	26	16	11
50-km Range	33	27	23	15	6	OK
PATROL-TO-INTERMEDIATE MOUNTAINTOP RELAY STATION RADIO LINKS						
100-km Range	31	27	45	34	26	20
75-km Range	21	17	36	24	16	11
50-km Range	10	7	25	13	6	OK
PATROL-TO-BEST MOUNTAINTOP RELAY STATION RADIO LINKS						
100-km Range	25	15	35	24	9	4
75-km Range	16	7	25	14	OK	OK
50-km Range	5	OK	13	3	OK	OK



size force, in a search and destroy operation, which encounters two battalions of red forces. The blue tactics were standard U.S. infantry practices as embodied in the INSURGE-II model. To reduce uncertainties, each red force was modeled as a single combat unit rather than as a headquarters and several subordinates. Consequently, command and control of each red force was treated as nearly perfect. No coordination between the two red forces was assumed or provided, however, other than exchange of intelligence via a "perfect" communication system.

One series of simulation runs were performed with the red forces employing a tactic believed to be representative of many VC actions in Viet Nam. Briefly, this tactic assumed that the red would attack when confronted by a small force, hold when confronted by a roughly equal force, and rapidly disengage and withdraw to a prepared position when confronted by a superior force. In half of the simulation runs of this series, a reasonably good performing blue communication system was used while in the other half of the runs system performance was somewhat degraded. Each run of the "good" or "bad" communication classes differed only in the random number sequence.

Next, a similar series of TACOS-II runs were performed in which the red withdrew slowly, rather than rapidly, toward the same prepared positions. Again both "good" and "bad" blue communication system performance and random number sequence differences were used.

The basic scenario was structured so that two counterinsurgent (blue) infantry battalions employed in a search and destroy operation would each encounter an enemy infantry unit (red) of near battalion size. One of these red units, during its withdrawal action, moved from one blue battalion zone of operation to the other. Such an action would require considerable coordination and control by higher headquarters and exercise much of the decision logic incorporated in the model.

The tactical action is centered in a valley, running from northwest to southeast, some 15 km west of Chu Lai in Viet Nam. Figure 4 illustrates the initial location of the principal forces. The terrain and vegetation data used in the link status model for these tests were taken from Tra Bong Sheet (6739 IV) of the 1:50,000 scale Army Map Service Series L7014. Figure 4 shows the disposition of all forces, except the blue aircraft, and artillery (which are located 15 km and 10 km to the east respectively) at the start of the simulated operation, 0600 hr.

The blue force consists of a brigade headquarters (unit 1) and battalions 1 and 2 whose headquarters are units 4 and 13, respectively. The zones of search responsibility for the front line companies and battalions of the blue force are indicated by the zone lines. The 1st battalion is responsible for zones 4, 5, and 6 to which front line companies, units 7, 6 and 5, have been respectively assigned. The 2nd battalion has assigned front line companies, units 16, 15 and 14 to cover zones 1, 2 and 3, respectively. Each battalion has one additional company in reserve (unit 8 of 1st Bn and unit 17 of the 2nd Bn) while two additional companies (units 2 and 3) are assigned as brigade reserves to accompany that headquarters until such time as they may be committed to the tactical action.

The insurgent (red) force, is composed of two battalion-sized units (units 31, 33), two small outposts (units 32 and 34), and unit 30, a small headquarters. Prior to the start of the sweep operation by the blue force, the red units were organizing for a major attack on nearby government installations. In the face of now present superior enemy, the red forces will conduct a withdrawal operation attempting to inflict casualties on the elements of the blue force.

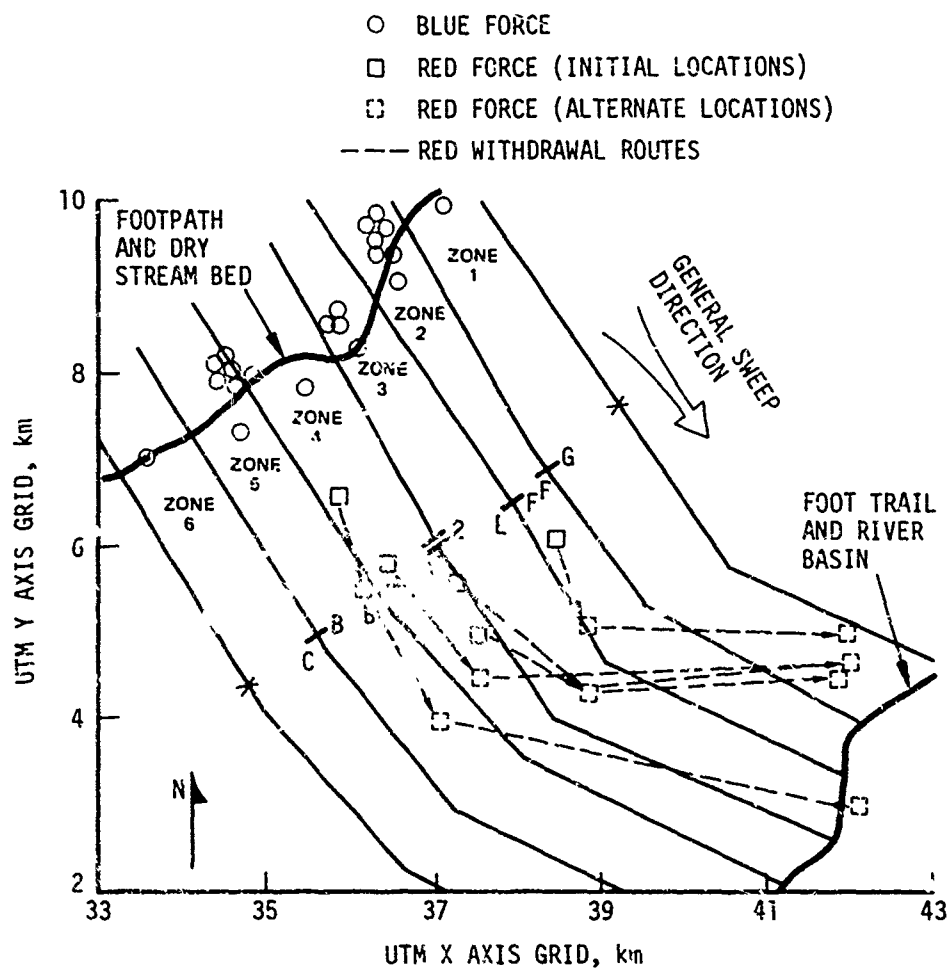


Figure 4. Search Zones and Disposition of Forces

In performing this withdrawal operation the red units will move along the dotted path shown in Fig. 4 to a series of alternate positions and, if forced to, will withdraw to their base camp in the jungle-covered mountains to the northeast of the valley. The initial location and the withdrawal routes of the red forces are not known, of course, by the blue force at the start of the sweep.

The blue forces tactical radio communication system as modeled in the test series is shown in Figure 5. (The red communication system was not explicitly modeled in any of the TACOS-II test runs. Instead all red messages were assumed to be complete at a time equal to their filing time plus the message length. Hence the red forces were considered as possessing a "perfect" communication system free of delays occasioned by message queueing, link outage, or operator reactions.)

Although each net is used primarily for a particular military function, other traffic types are often routed through one or more links of a net to expedite communication. In the message processing model, a message was allowed to take an alternate route in a net other than its most desirable net (or link type) only if no possible route existed using the most desirable link type. For example, command messages could be sent on the artillery nets only if no single or multiple link routing was possible via the command nets. If such a route was possible but busy with equal or higher precedence traffic, the command message was recycled until it could be processed on a command net.

The area of operations consisted primarily of jungle with a scattering of open forest, scrub brush and clearings. In modeling the series of tests referred to as "good" communications, the jungle was represented as a lossy dielectric slab 15 meters in thickness (believed typical for this region) and the message processing delays were those believed typical of alert radio operating personnel. For the test runs classed as typical of "bad" communication conditions, the jungle slab thickness was increased to 30 meters and operator reaction times were increased modestly. The same radio nets and equipment were used in all runs.

A total of 16 TACOS-II test runs were performed. The detailed time sequence of actions and the resulting casualties as determined by the computer were different for each run. The general course of the action, however, was the same for all test runs associated with each red withdrawal tactic (rapid or slow). Half of the TACOS-II runs modeled the red forces with rapid withdrawal actions and the remainder with a slow withdrawal tactic. Each of these groups of test runs was further divided according to the performance of the blue communication system--either "good" or "bad". The four TACOS-II runs in each subgroup differed only in terms of the random number sequence employed.

Figure 6 shows that, with the true jungle (i.e., "good" communication) runs, all links in the system were operable at least 50% of the time and 40-50% of the system links remained operable 100% of the time. With the runs employing the taller more severe jungle (i.e., "bad" communication), only about 30% of the system links were always operable. Viewed another way, in the "good" runs at least 90% of the links in the system were in working order 80% of the time, while in the "bad" runs only 50% of the links were operable. Viewed another way, in the "good" runs at least 90% of the links in the system were in working order 80% of the time, while in the "bad" runs only 50% of the links were operable 80% of the time.

FIG. 5 RADIO COMMUNICATION NETS

RADIO Net No.	Type	Function	Member Units	AN Radio Type	MOD	Freq. MHz	Antenna
1	1	Brigade Command and Operations	22,25	VRC-12	FM	40.0	3-m whip on AC-292 Mast
			1,4,13	PRC-25	FM	40.0	3-m whip at back-pack height
			2,3	PRC-25	FM	40.0	1-m whip at back-pack height
2	1	1st Bn Command and Operations	4,11,12	PRC-25	FM	42.3	3-m whip at back-pack height
			2,3,5,6,7,8,9,10	PRC-25	FM	42.3	1-m whip at back-pack height
3	1	2nd Bn Command and Operations	13,20,21	PRC-25	FM	45.5	3-m whip at back-pack height
			2,3,14,15,16,17	PRC-25	FM	45.5	1-m whip at back-pack height
			18,19				
4	5	Air Request	1,25	PRC-47	AM SSB	4.5	10-m vertical whip, base at ground level
			4,5,6,7,8,13,14, 15,16,17	PRC-47	AM SSB	4.5	3-m whip at back-pack height
5	6	Air/Ground	1,2,3,4,5,6,7,8, 9,10,13,14,15,16, 17,18,19,25	PRC-41	AM	231.0	1/4 coaxial stub 2 m above ground
		Coordination	26,28	ARC-27	AM	231.0	1/4 coaxial stub on aircraft
6	6	Air/Ground	1,2,3,4,5,6, 7,8,9,10,13, 14,15,16,17, 18,19,25	PRC-41	AM	222.0	1/4 coaxial stub 2 m above ground
		Coordination	27,29	ARC-27	AM	222.0	1/4 coaxial stub on aircraft
7	4	Artillery Fire Coordination	22,23	VRC-12	FM	36.2	3-m whip on AC-292 mast
			1,4,13	PRC-25	FM	36.2	3-m whip at back-pack height
			2,3,5,6,7,8,9,10, 14,15,16,17,18,19	PRC-25	FM	36.2	1-m whip at back-pack height
8	4	Artillery Fire Coordination	22,24	VRC-12	FM	37.1	3-m whip on AC-292 mast
			1,4,13	PRC-25	FM	37.1	3-m whip at back-pack height
			2,3,5,6,7,8,9,10, 14,15,16,17,18,19	PRC-25	FM	37.1	1-m whip at back-pack height
9	4	Artillery Request	22	VRC-12	FM	36.6	3-m whip on AC-292 mast
			1,4,13	PRC-25	FM	36.6	3-m whip at back-pack height
			2,3,5,6,7,8,9,10, 14,15,16,17,18,19	PRC-25	FM	36.6	1-m whip at back-pack height
10	4	1st Battalion	4,11,12	PRC-25	FM	38.0	3-m whip at back-pack height
		Fire Control	2,3,5,6,7,8,9,10	PRC-25	FM	38.0	1-m whip at back-pack height
11	4	2nd Battalion	13,20,21	PRC-25	FM	37.5	3-m whip at back-pack height
		Fire Control	2,3,14,15,16,17, 18,19	PRC-25	FM	37.5	1-m whip at back-pack height



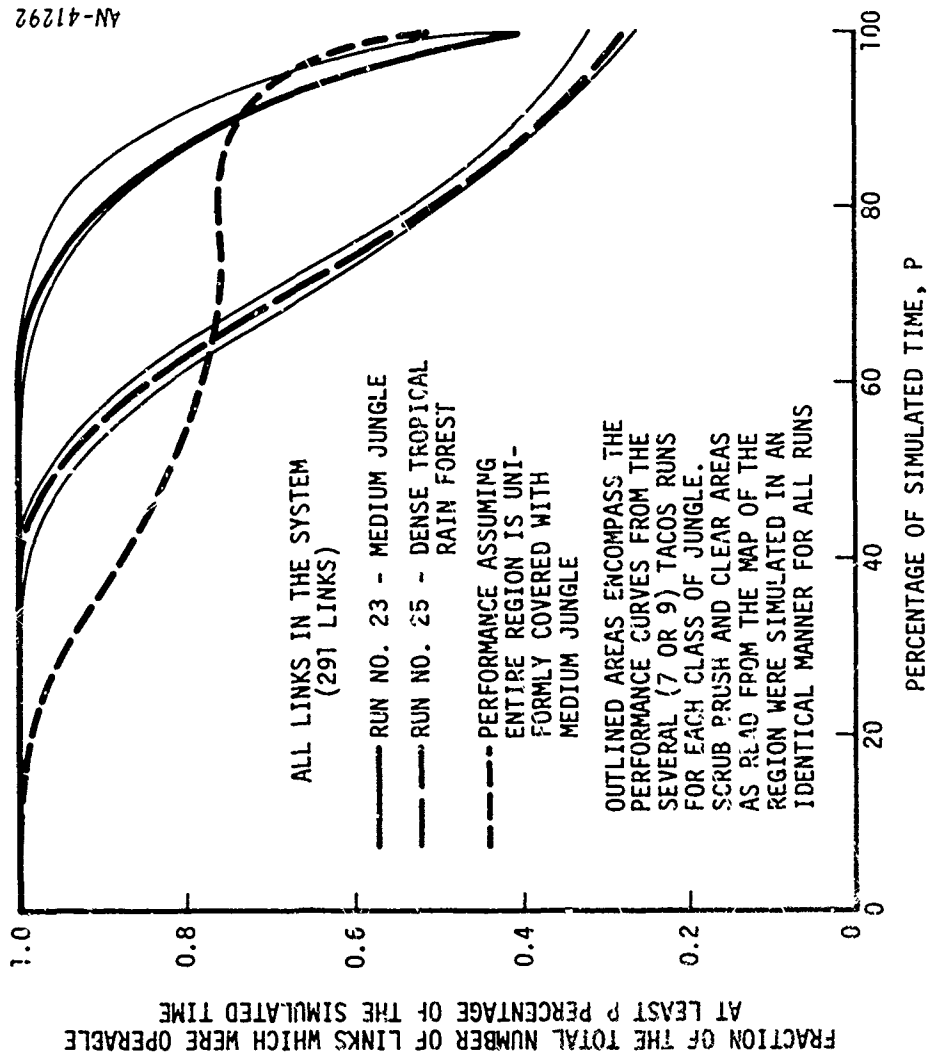


Figure 6. Summary of Communication Link Performance

The light lines surrounding the performance curve for each type of jungle in Fig. 6 indicate the variability in performance which resulted from the different random number sequences employed. Clearly, with the scenario used, the probabilistic calculations of link performance in TACOS-II produced no significant differences in the overall link operability data as deduced from any given run compared to any other run in which the hardware and propagation environment descriptors were held constant. Of course, another scenario, involving friendly combat units more widely dispersed or different terrain with more variations in topography or vegetation, could yield more variability in the link performance data.

Also shown in Fig. 6 (as a dotted curve) is the link performance obtained from an early TACOS-II test in which the entire map was assumed to be uniformly covered with the "true" jungle.\*

It might be inferred that communications would necessarily be poorer for the "bad" condition than for the "good" from the data shown in Figure 6; however, just how much poorer can be seen in a comparison of the message delays encountered under each situation. Figure 7 shows message delay distributions for the "good" situation and Figure 8 for the "bad". It can be seen that the median message delay for "good" communications was of the order of 1.8 minutes while for the "bad" (Fig. 8) it was of the order of 5 minutes. Similar comparisons can be made for high precedence orders and reports (message type 1) and intermediate precedence intelligence messages (type 5).

A great variety of other communication system performance data was also generated which permitted examinations of individual station, link, and net delays, traffic loads, etc. However, the significance of these data is not clear unless it can be related to tactical performance.

The simulation produces a variety of tactical performance information. Measures which could be examined include: times to reach objectives, effectiveness and efficiency of use of organic and support fire, casualties, etc.

Figure 9 shows a plot of blue casualties versus red casualties for all the test cases wherein the red forces employed the rapid withdrawal tactic. The solid contour lines represent the location and shape of the distribution of tactical results that might be expected in the "good" communication situation; the dotted contours those for the "bad" (assuming that the modest sample of four runs in each distribution adequately describe its mean value and dispersion). Since these two distributions are distinctly separate, it may be inferred that "good" communications had a significant part in causing the blue tactical successes.

Figure 10 shows the same comparison for those cases where the red forces employed a slow withdrawal tactic. Although the blue forces again inflicted more casualties than they received, the difference between tactical performance under "good" communication conditions is not greatly different from that under "bad" communication conditions.

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\* No variability is shown since the plotted data resulted from a single TACOS-II test.

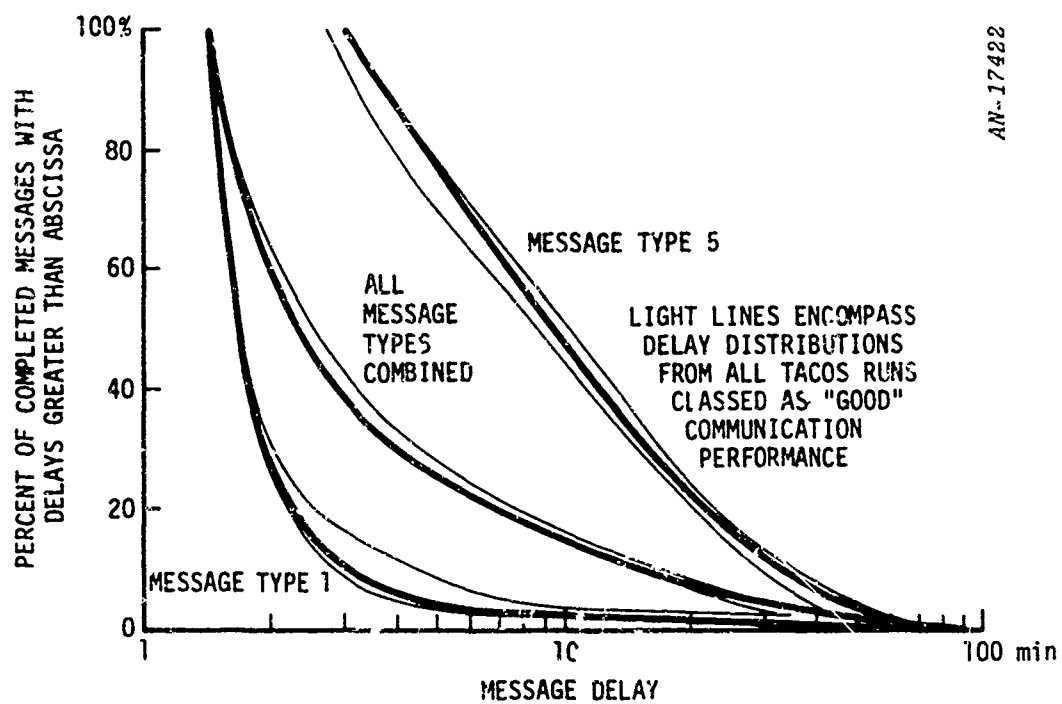


Figure 7. Message Delay Distributions: Good Communications (from TACOS-II Run No. 23)

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I-I-14

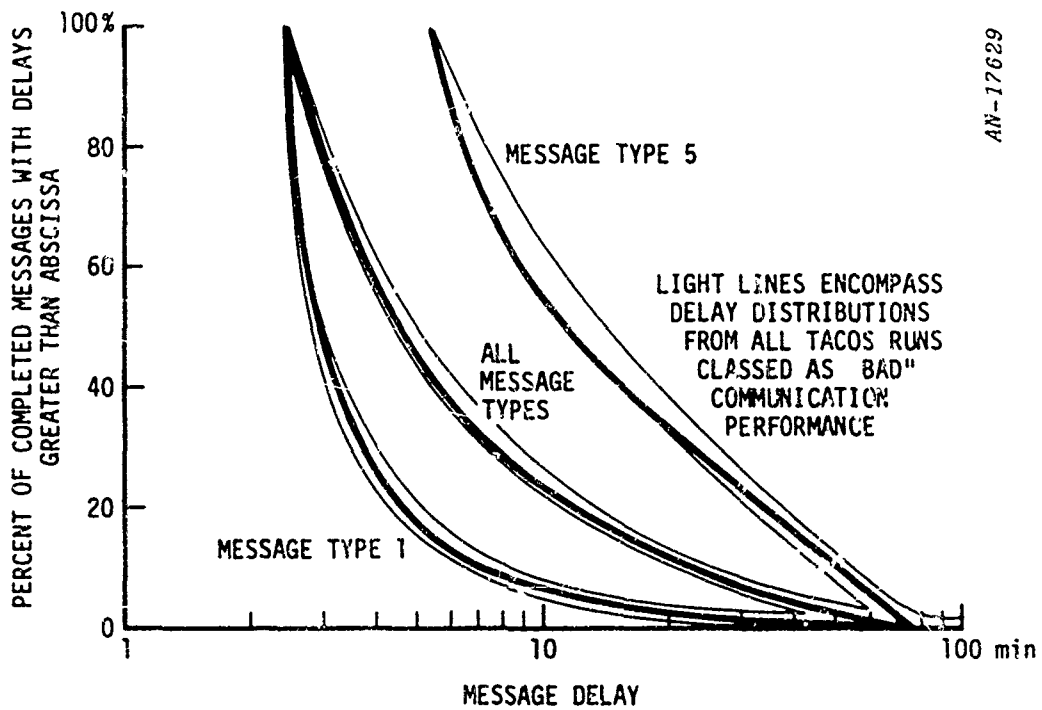


Figure 8. Message Delay Distributions: "Bad" Communications (from TACOS-II Run No. 25)

FROM TACOS-2 SIMULATION

RAPID RED WITHDRAWAL TACTIC

AN-41293

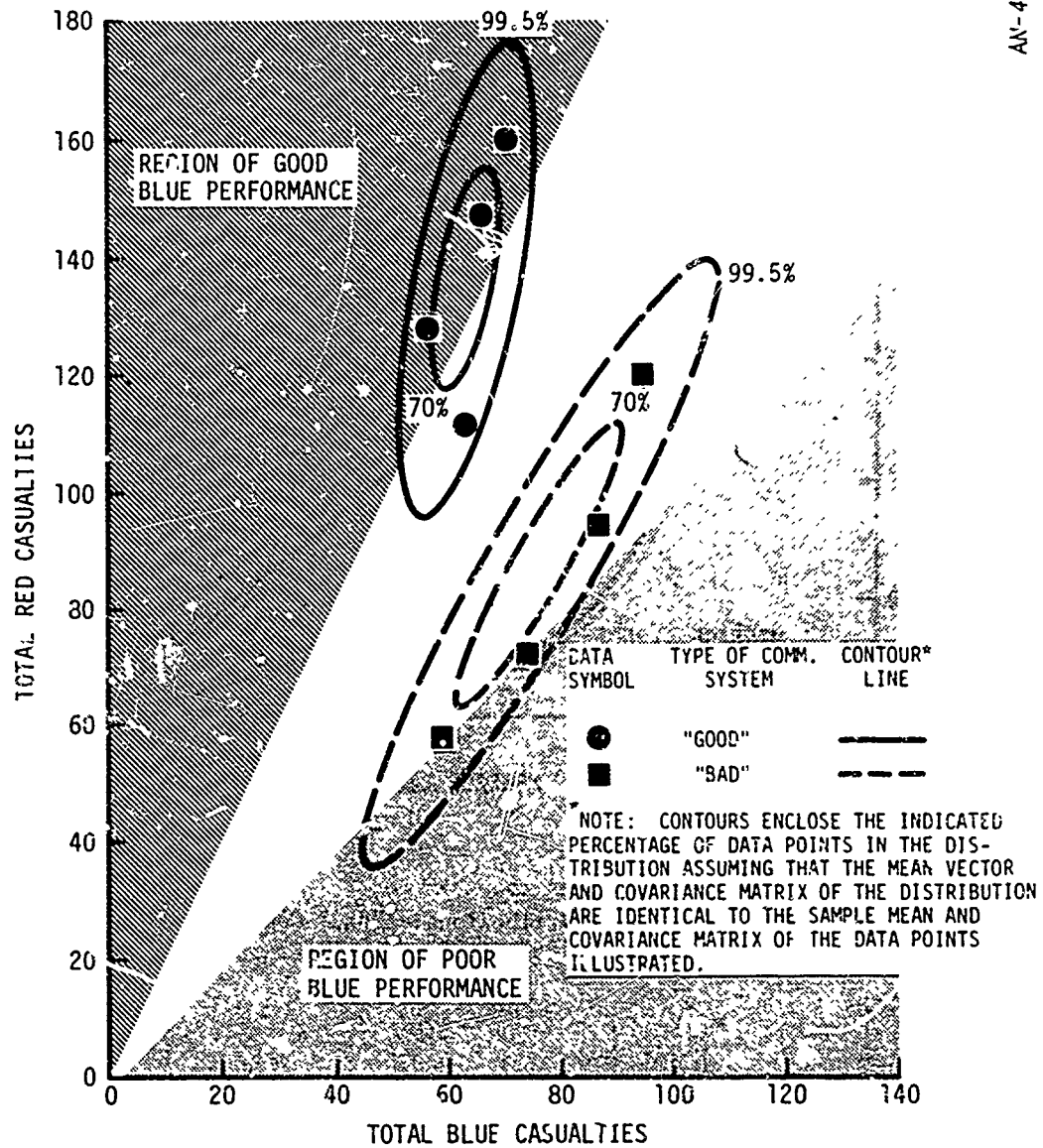


Figure 9. Red Versus Blue Casualties

FROM TACOS-II SIMULATION

SLOW RED WITHDRAWAL TACTIC

AN-4129

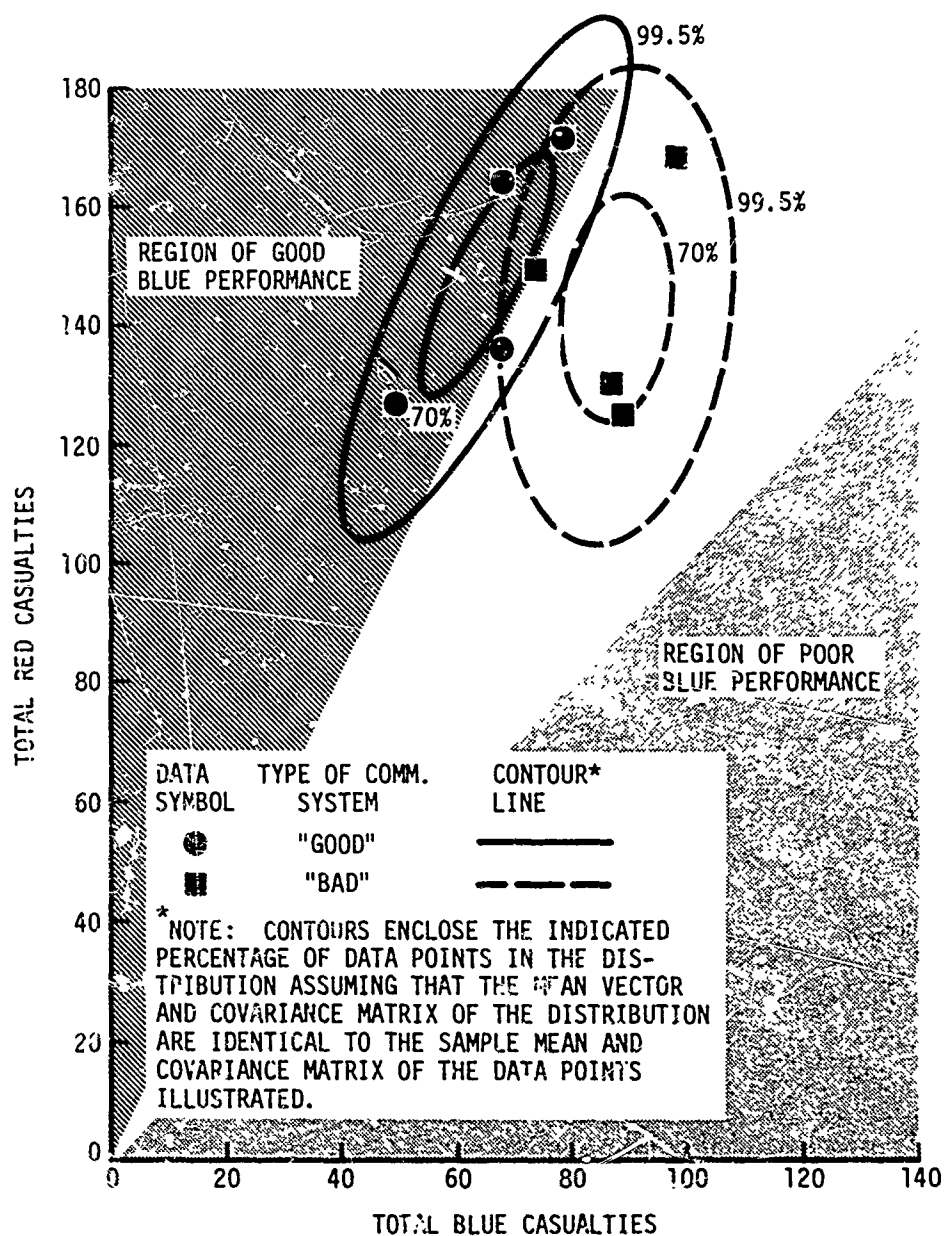


Figure 10. Red Versus Blue Casualties

I-I-17

The conclusions drawn from these tests are (1) that the Monte Carlo techniques used in the simulation do provide probable communication system and tactical performance values, and (2) that communications system performance measures alone cannot always be used to infer their value to tactical performance.

PHYSICAL MODELING TECHNIQUES

by

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Presented at

Workshop on Radio Systems  
in Forested and/or Vegetated Environments  
US Army Communications Command  
Fort Huachuca, Arizona

6-9 November 1973

I-J-i

117<

SUMMARY: Physical Modelling (The performance as RF antennas of trees and vegetation in jungles and man-made structures in urban areas)

Kurt Ikrath and William Kennebeck  
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U. S. Army Electronics Command, Fort Monmouth, New Jersey 07703

A model is a standard for imitation or comparison, i.e. a representation, generally in miniature, to show the construction or to serve as a copy of a physical system or phenomenon, in our case, HF radio communications in jungles. Physical models of HF radio communications in jungles serve a different purpose than theoretical or otherwise convenient conjectures about the propagation of HF radio waves over jungle-covered terrains. The purpose of the physical models which are described here becomes evident by considering the practical realization of "Tree Telephony and Telegraphy," as envisioned in 1904 by Major George O. Squire, U. S. Army Signal Corps (Ref. 1).

The practical realization of tree telephony and telegraphy in jungle environments was demonstrated by comparing the performance of a typical whip antenna as shown in Fig. 1 (Fig. 9 of Ref. 2) with that of trees as antennas excited by toroid-shaped Hybrid Electromagnetic Antenna Couplers (HEMAC's) as shown in Fig. 2 (Fig. 7 of Ref. 2). The performance as transmitter antennas, of the whip and of jungle trees powered by the same PRC-74 set are seen in Fig. 3 (Fig. 16 of Ref. 2).

The divergency of the decays with distance from the XMTR of signals emitted by the whip antenna and by HEMAC-coupled jungle trees (Fig. 3) could be dismissed as statistical coincidences, were it not for the results of previous experiments in deciduous forests in New Jersey. Typical samples of these experimental results are described by the radiation pattern reliefs and the corresponding total radio illumination (TRI) values\* in Figs. 4 to 6 (Figs. 5, 7, and 9 of Ref. 3).

The fact that this divergency and the relative-to-the-whip superior performance of HEMAC-coupled trees as antennas is not an anomaly is seen by data from the Gamboa Jungle Area in Figs. 7-10 (Figs. 17, 21, 22, and 24 of Ref. 2). The divergency between signal-versus-distance decays, as sensed by the whip and by different hemac-coupled jungle trees, particularly after heavy rains in dripping wet jungles (Fig. 11) is self-evident. While omitting further details here, which are given in Ref. 2, it should be pointed out that in the Gamboa, Panama Canal Zone, jungle tests, the transmitter and receiver whip antennas were privileged by having been set up on a narrow dirt road (Fig. 13) rather than in small jungle clearings (jungle holes) cut out by machetes from the dense underbrush and vegetation.

The explanation and verification of this divergency and of the corresponding apparently antenna-dependent signal-versus-distance decay between transmitter and receiver locations in dense forest-covered terrains became the primary objective of our physical modelling in the laboratory.

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\* Integral of radiation pattern

The live model vegetation in the form of shrubs, grasses, and herbs seen in Fig. 11 (Fig. 1 of Ref. 4); the miniature whip; shielded magnetic loop and hemac toroid (Figs. 2-5 of Ref. 4); and the results of microwave model transmission measurements given in Figs. 12-17 (Figs. 7-12 of Ref. 4) verify and explain the observed divergency as follows. The linear one-dimensional electrical whip antenna is least qualified; the circular two-dimensional, shielded magnetic loop antenna is better qualified; and the toroidal three-dimensional hybrid electromagnetic antenna coupler is best qualified to match conventional radio transmitters and receivers to the polarization and electromagnetic field impedance-diffusing environments formed by RF leakage coupled forest cavities under the rough and leaky foliage canopy roofs of jungle forests.

However, microwave frequencies and the live vegetation of the miniature jungle model cannot be used to model the enhancement of RF leakage radiation from forest cavities by wrapping hemacs around the pillar of the forest canopy roofs, i.e., around the tree trunks (Figs. 3-6 and 25 of Ref. 5).

The fact that the local tree configurations which form the forest cavities govern the mutual coupling between the directly energized hemac-coupled tree and adjacent trees and consequently the directivity of RF radiation is self-evident. The shapes of the radiation patterns from various trees in forests in New Jersey have shown that the directivities of RF radiation from forest sites can be traced to "dominant natural tree loops" and to certain terrain features (Refs. 5 and 6). Similarly, parasitic coupling between the directly energized whip antenna and adjacent tree configurations manifest themselves in dominant "whip-tree loops" and corresponding shapes of the radiation patterns (Refs. 4, 5, and 8).

However, military radio communications in jungle-covered terrains require that the control over the directivity of RF radiation from forest sites must not be left to local forest structures, but must be given to the radio operators. The degrees of success achieved in controlling the directivity of HF ground and skywave transmissions with the aid of a phased hemac-coupled twin-forest-tree XMTR array in Fig. 18 (Fig. 1 in Ref. 7; Fig. 2 in Ref. 8) are quantified by the ground wave radiation patterns in Figs. 19-21 in conjunction with the map of the receiver locations in relation to the forest XMTR site in Fig. 22 (Figs. 7-10 of Ref. 7). Reference 7 also introduces a close relative of the natural tropical jungle, namely, the man-made urban jungle. The coexistence in this jungle of shade trees and of metal lantern poles gives the opportunity to compare their antenna characteristics. Of particular interest with regard to ground and skywave transmissions is the response of trees and of lantern poles to topside incident radiation from an aerial tramway transmitter gondola. The experimental setup and the self-evident results are shown in Figs. 23-25 (Figs. 32, 36, and 38 of Ref. 7). Like the live vegetation of natural jungles, the steel-concrete structures of urban jungles form hostile environments for conventional tactical radio communications. The live natural jungle vegetation and the lifeless urban jungle structures are also close relatives in the military sense; they are both a camouflaged haven for guerrilla forces.

The reasons for this dilemma are that radio antennas extending from a soldier's back-pack set, from military vehicles, shelters, and command post installations are visual designators of prime targets for attacks by

guerrillas who are camouflaged in this jungle; and radio signals emitted from these antennas are perfect trigger and homing beacons for mines and missiles.

Thus it is evident that particularly in urban jungle wars, tactical military communications devices and radio transmissions must be camouflaged visually and electronically.

As described in Refs. 7, 8, and 9, it is logical to exploit for these purposes the electromagnetic characteristics of live and of lifeless stationary, mobile, and airborne structures that shape and are shaped by man, including man himself. The role of man in HF emission from a human body camouflaged and human body coupled (1 watt) radio XMTR is revealed by the pictures and the data in Figs. 26-31 (Figs. 1, 2, and 4A-4C of Ref. 9).

The data (Figs. 28-31) reveal that the human body can serve as a relatively efficient camouflaged RF antenna if one does not couple to the belly. Evidently, in contrast to the tissues under the bark of tree trunks, the tissues underneath the waistline portion of the body are RF absorbers. The effectiveness of the human body XMTR showed up in those natural and man-made jungle environments to which the whip cannot adapt itself mechanically and electrically.

#### ACKNOWLEDGMENTS

Research and development leading to the exploitation as radio antennas of live vegetation in natural jungle environments have been guided initially by Col. J. P. Dobbins during his tour of duty as Director of ECOM's Communications/ADP Laboratory. Col. J. D. Mitchell, the present Director of the Laboratory, is providing overall guidance and special technical advice for the application of HEMAC techniques to the exploitation as RF antennas and transmission media of diverse structures in man-made urban jungle environments.

Command-management personnel of the U. S. Army Tropical Test Center, Fort Clayton, Panama Canal Zone, in particular, Maj. Wilkenson, Capt. Alaiza, PFC Tench, and Messrs. Wilson and Blades provided technical and logistical support for the various radio transmission experiments in the Chiva Chiva and Gamboa A.2 Test Area, Panama Canal Zone.

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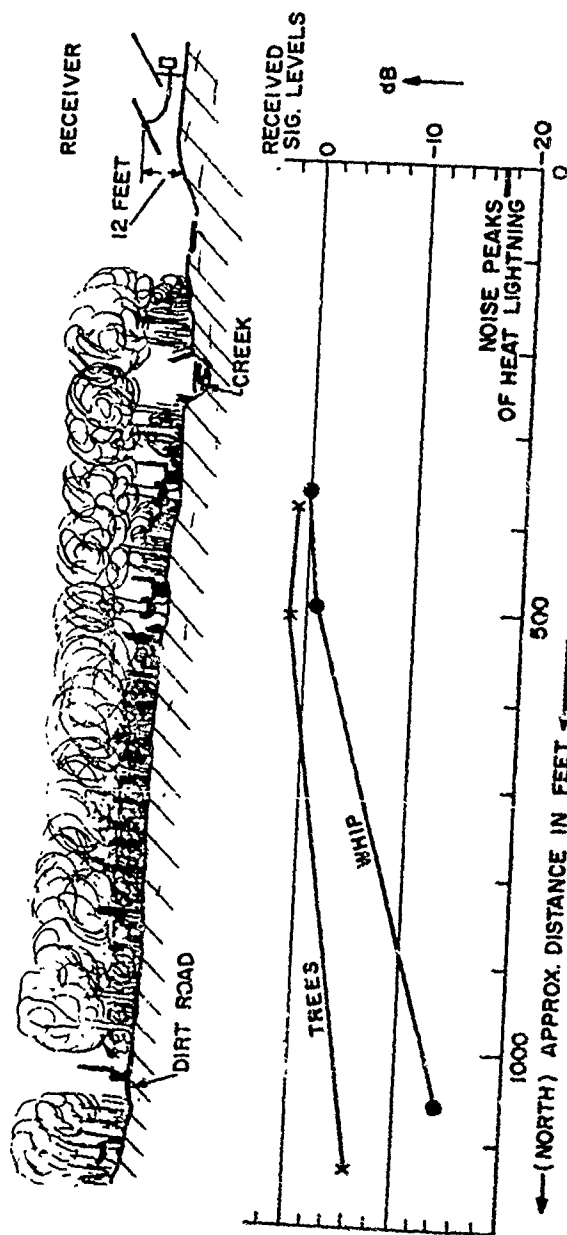
FIG. 9 PRC-74 Set + Whip At Jungle  
Hole Site  
Chiva Chiva Area, Panama C.Z.  
September 71

Fig. 1 I-J-5



FIG. 7 HEMAC Toroid Coupled Tree and  
PRG-74 Set At Jungle Hole Site  
Chiva Chiva Area, Panama C.Z.  
September 71

Fig. 2 I-3-6



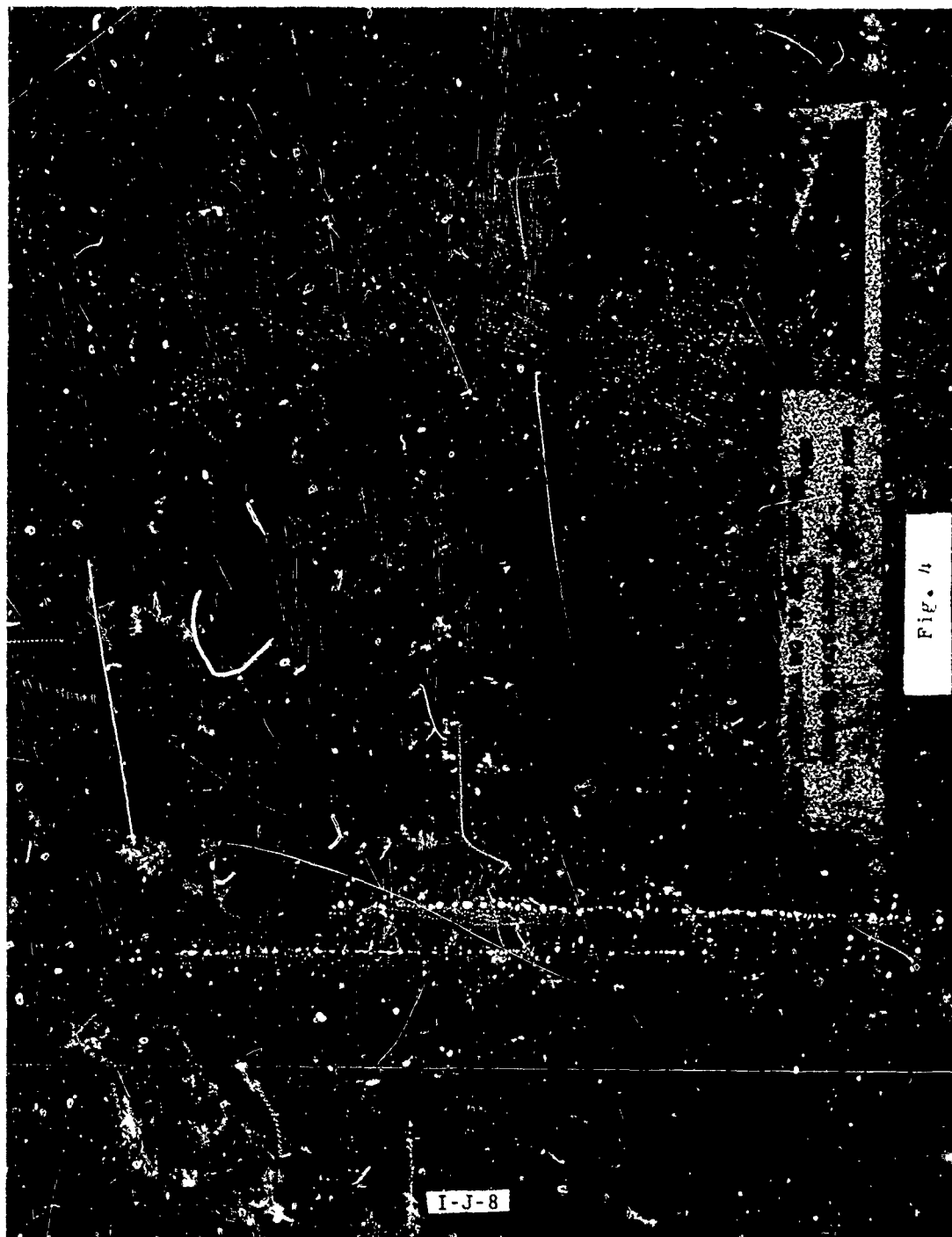
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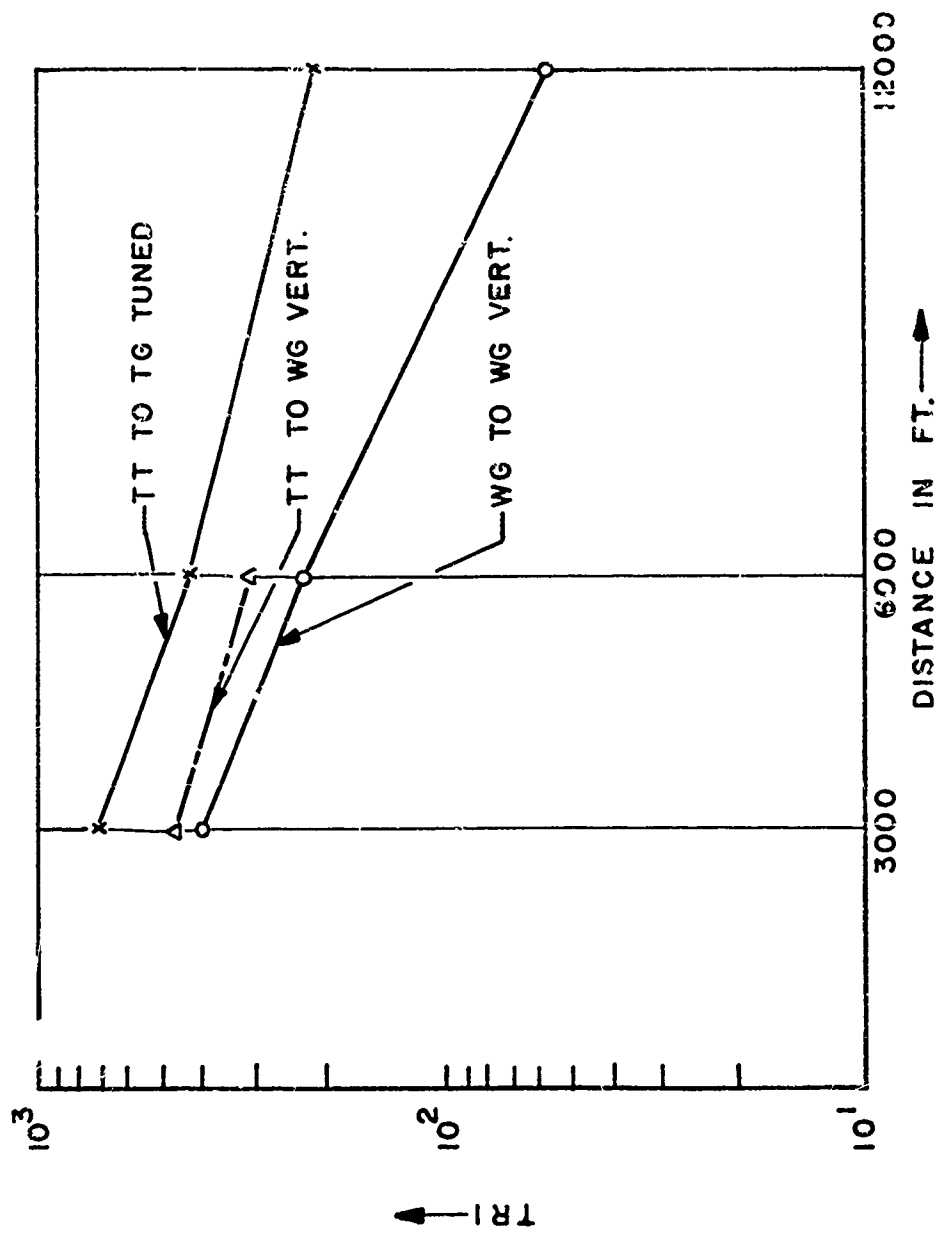
FOOTNOTES: (1) HOR. REC. DIPOLE CUT FOR 6.050 MHz  
 (2) VIA. SERIES TUNED MATCHBOX.  
 (3) TUNE-MATCHING CONTROLS ADJUSTED IN EACH CASE  
 FOR .MAX. POSSIBLE RF OUTPUT INDICATION BY PRC-74 METER.  
 RELATIVE LEVELS IN dB AS RECEIVED  
 WITH HORIZONTAL WIRE DIPOLE ANTENNA(1)  
 OF 4.650 MHz CW SIGNALS RADIATED FROM  
 RESPECTIVELY THE PRC-74 WHIP AND HEMAC  
 TOROID COUPLED JUNGLE TREES(2) POWERED  
 BY IDENTICAL PRC-74 TRANSCEIVER SET(3).

CHIVA-CHIVA TEST AREA 8/26/71

Fig. 3  
 Relative Levels In dB As  
 Received With Horizontal Wire  
 Dipole Antenna of 4.000 MHz  
 CW Signals Radiated From  
 Respectively the PRC-74 Whip  
 And HEMAC Toroid Coupled Jungle  
 Trees Powered by Identical  
 PRC-74  
 Chiva Chiva Area  
 September 71







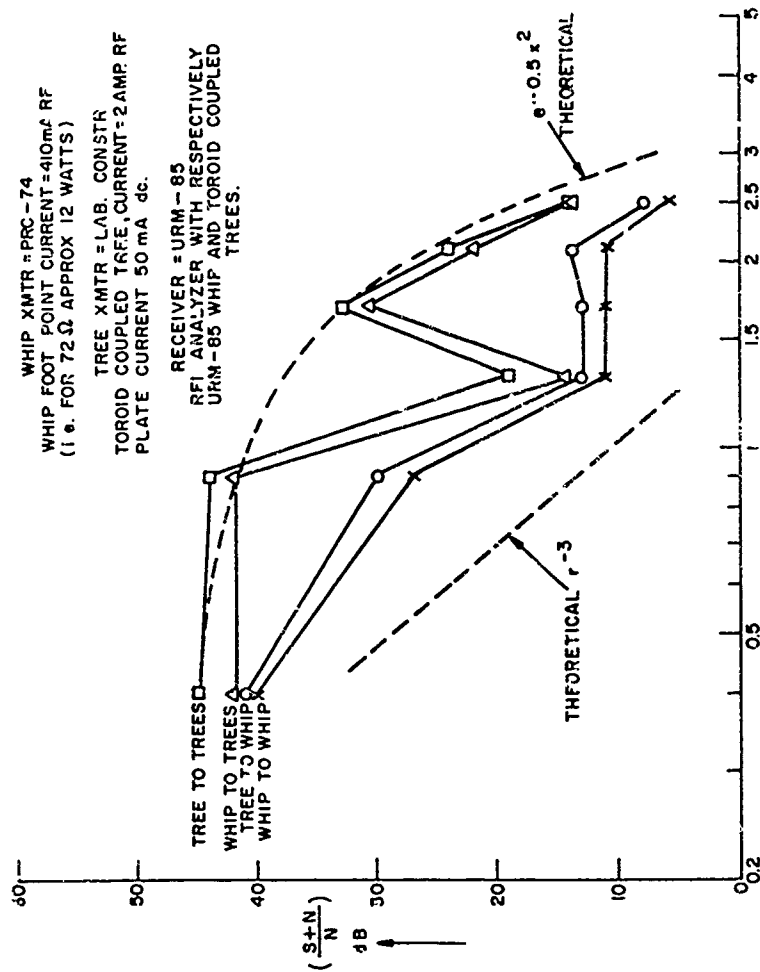
TRI VALUES IN dB VERSUS DISTANCE IN FEET  
 (TT: Toroid Tree; TG: Toroid Ground; WG: Whip Ground)

↑ TRI

Fig. 6

I-J-10





GAMBOA PANAMA - SUNDAY AFTERNOON SEPT 5, 1971  
CLOUDY - JUNGLE VEGETATION DRIPPING WET AFTER HEAVY RAINFALL  
4.650 MHz SIGNAL + NOISE / NOISE IN dB VERSUS DISTANCE FROM XMTR SITE.

Fig. 8 4.650 MHz Signal + Noise/Noise  
In dB Versus Distance From XMTR  
Site. Jungle Vegetation Dripping  
Wet  
Gamboa A.2 Area, Panama C.Z.  
September 5, 71

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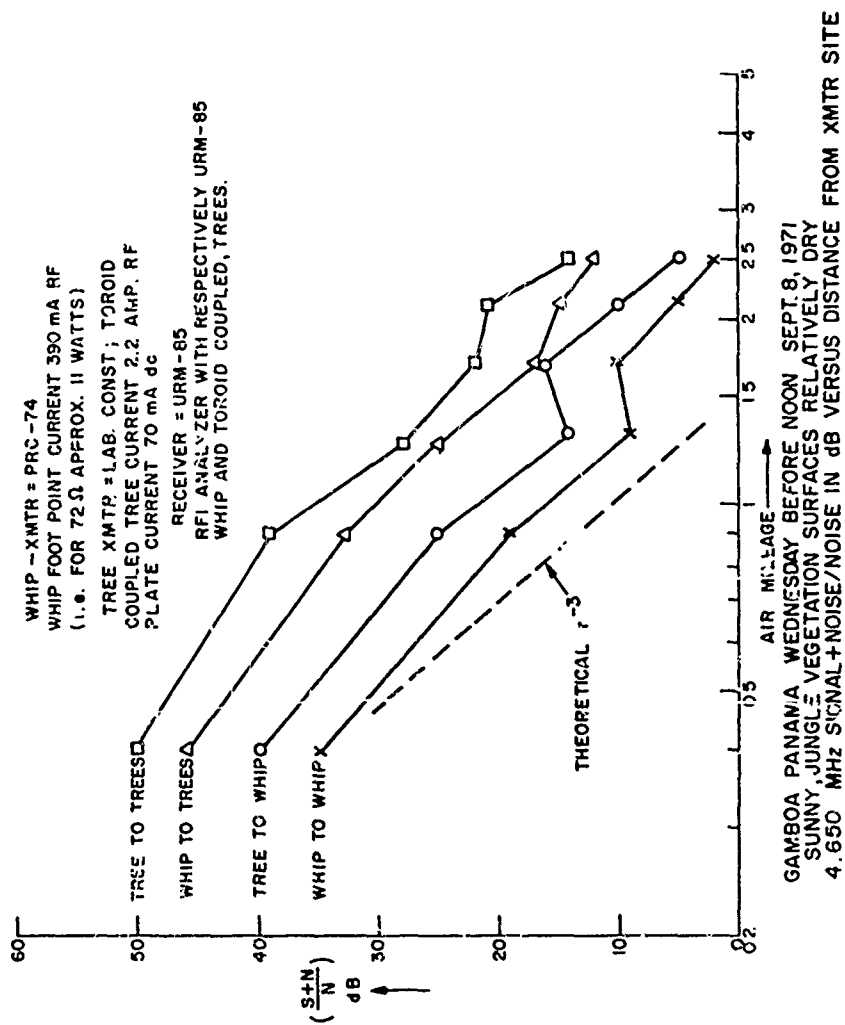


Fig. 9 4.650 MHz Signal + Noise/Noise  
in dB Versus Distance From XMTR  
Site. Jungle Vegetation Dry.  
Gamboa A.2 Area, Panama C.Z.  
September 8, 71

I-J-13

130<

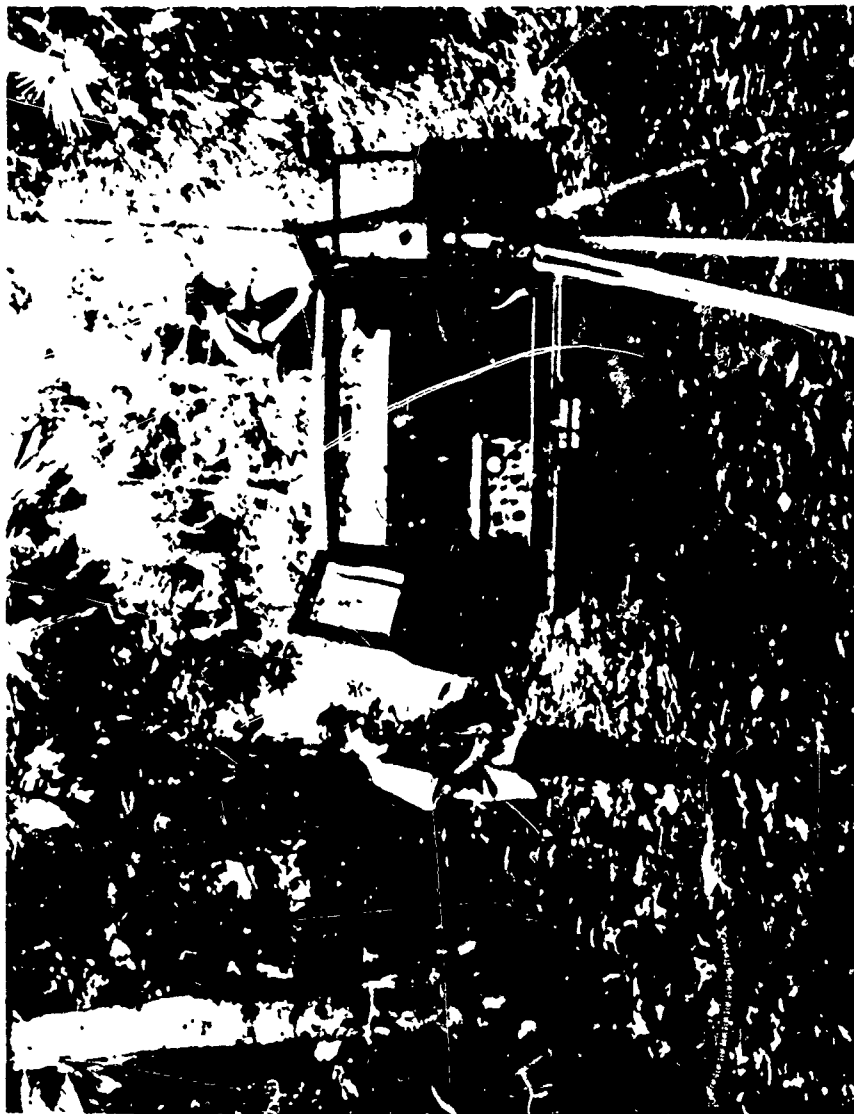


FIG. 24 Typical Receiver Set-up: From  
Left To Right: HEAC Toroid  
Coupled Line, PKC-74 Set + Whip,  
URM-85 Field Strength Meter In  
The Vehicle, URM-85 Whip On  
Tripod.  
Gamboa A-2 Area, Panama C.Z.  
September, 71

Fig.10

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JUNGLE MODEL - OVERALL VIEW

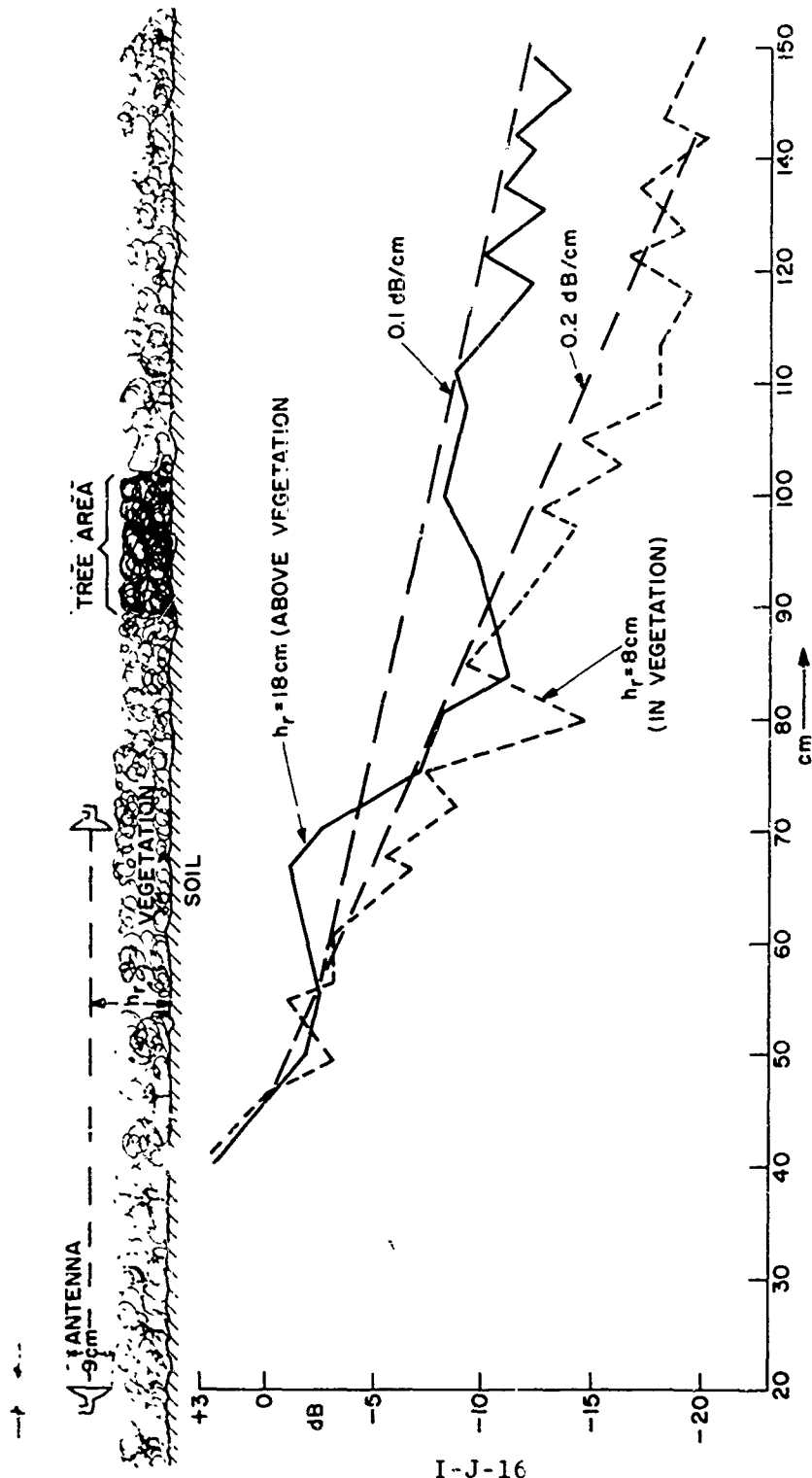


Fig.12

JUNGLE MODEL: 6.5 GHz CW SIGNAL DECAY VERSUS DISTANCE BETWEEN IDENTICAL  
TYPE XMTR AND RECEIVER HORN ANTENNAS ABOVE ( $h_r = 18 \text{ cm}$ ) AND INSIDE  
( $h_r = 8 \text{ cm}$ ) VEGETATION OF HIGH  $h_{veg} \leq 16 \text{ cm}$  MARCH 17, 1971

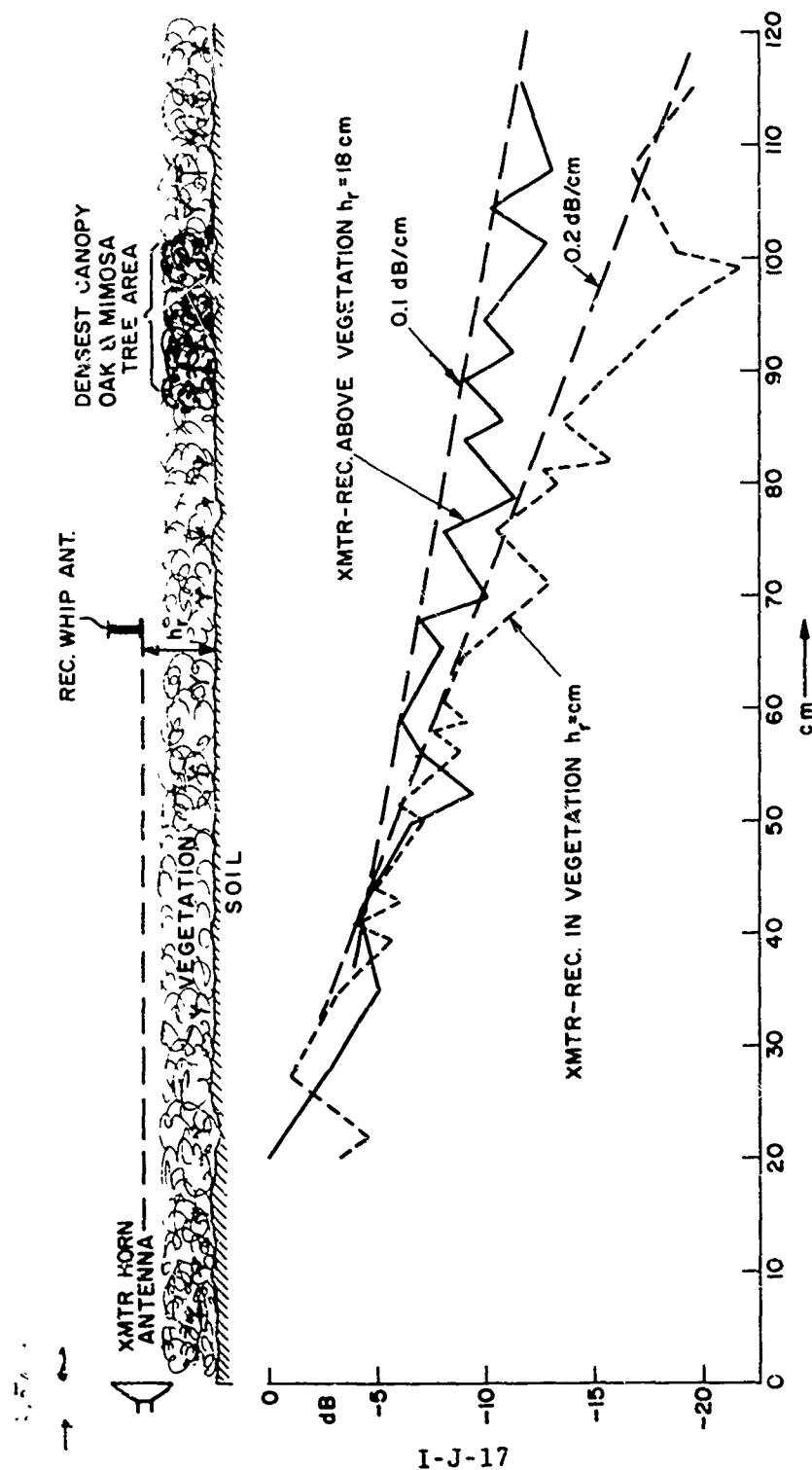


Fig. 13 JUNGLE MODEL: 6.5 GHz CW SIGNAL DECAY VERSUS DISTANCE FROM XMTR-ANTENNA.  
(REL. MAX-MIN.) MEASURED WITH VERTICAL WHIP RECEIVER ANTENNA ABOVE ( $h_r = 18$  cm)  
AND INSIDE ( $h_r = 7$  cm) VEGETATION OF HIGH  $h_{veg} \leq 16$  cm; MARCH 3, 1971.

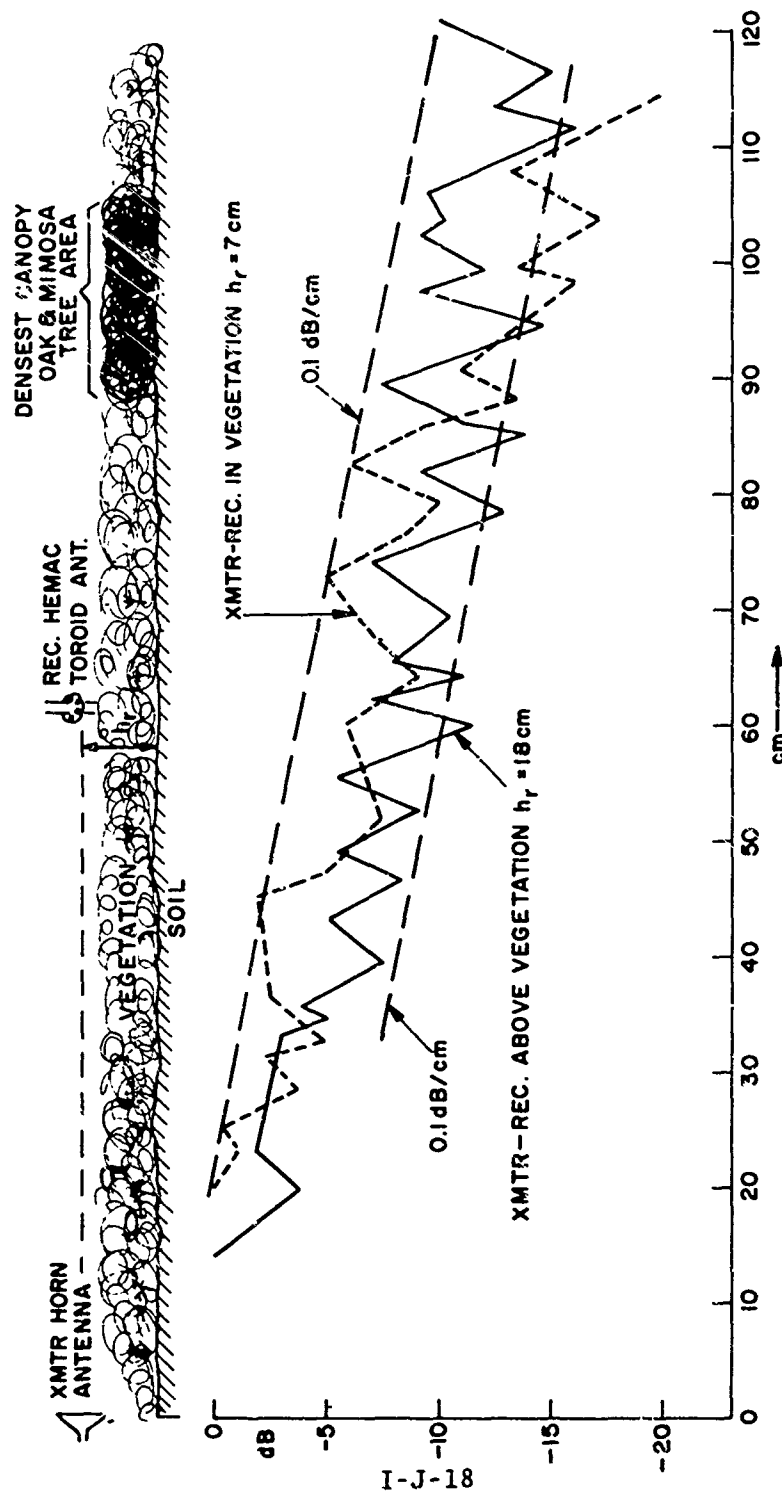


Fig.14 JUNGLE MODEL: 6.5 GHz CW SIGNAL DECAY VERSUS DISTANCE FROM XMTR-ANTENNA;  
(REL. MAX-MIN.) MEASURED WITH "HEMAC" TOROID ANTENNA ABOVE ( $h_r = 18 \text{ cm}$ ) AND INSIDE  
( $h_r = 7 \text{ cm}$ ) VEGETATION OF HIGH  $h_{\text{veg}} \leq 16 \text{ cm}$ ; MARCH 5, 1971.

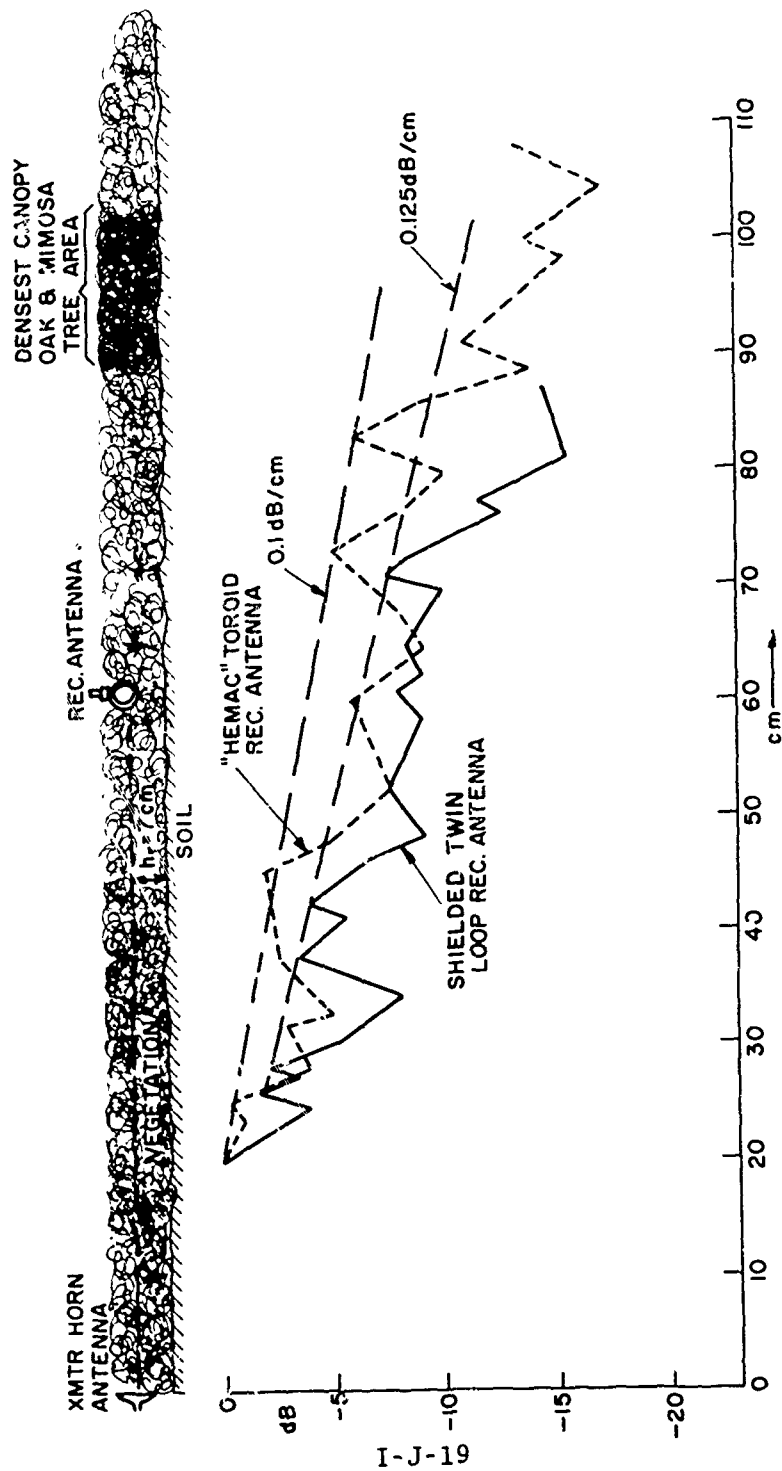


Fig. 15 JUNGLE MODEL: 6.5 GHz CW SIGNAL DECAY VERSUS DISTANCE FROM XMTR-ANTENNA. (REL. MAX. - MIN.) MEASURED WITH "SHIELDED TWIN LOOP" AND "HEMAC" TOROID RECEIVER ANTENNA INSIDE ( $h_v = 7\text{cm}$ ) VEGETATION HEIGHT  $h_{veg} \leq 16\text{cm}$ ; MARCH 4, 1971

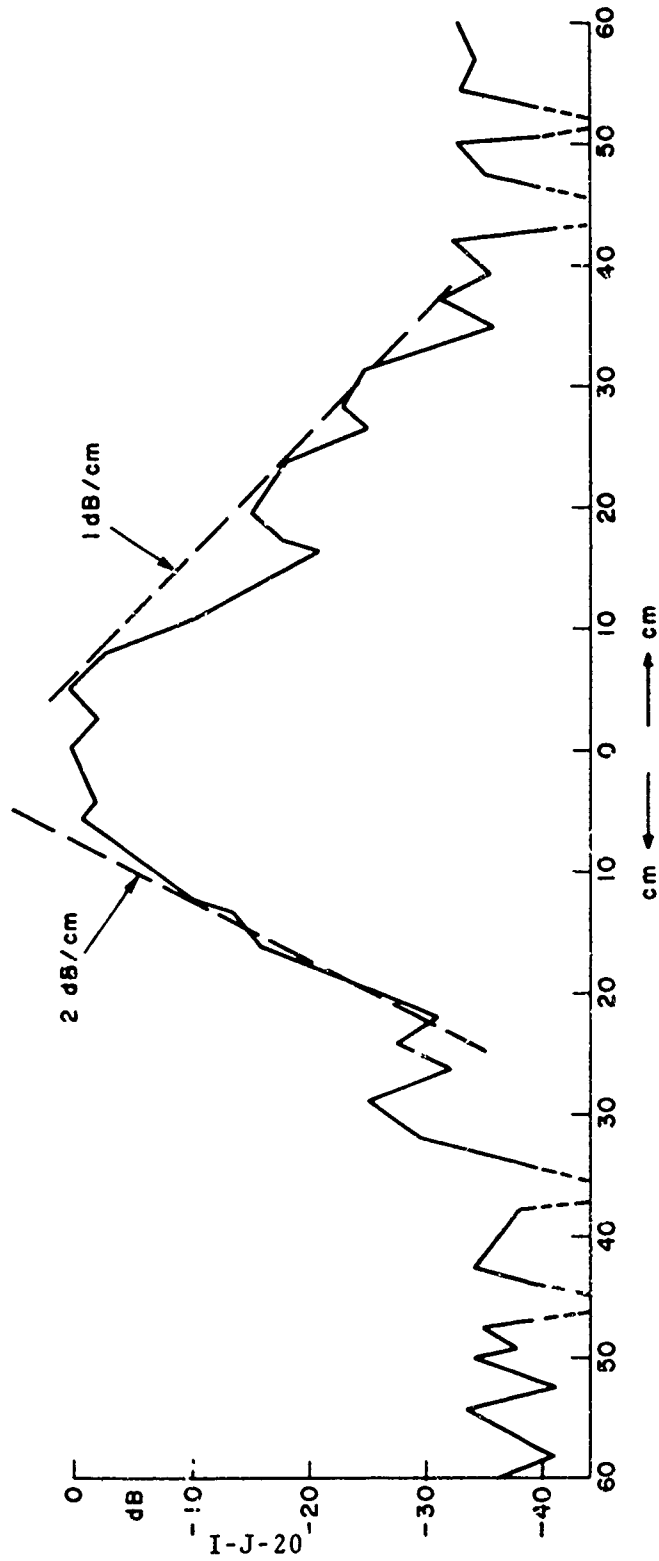
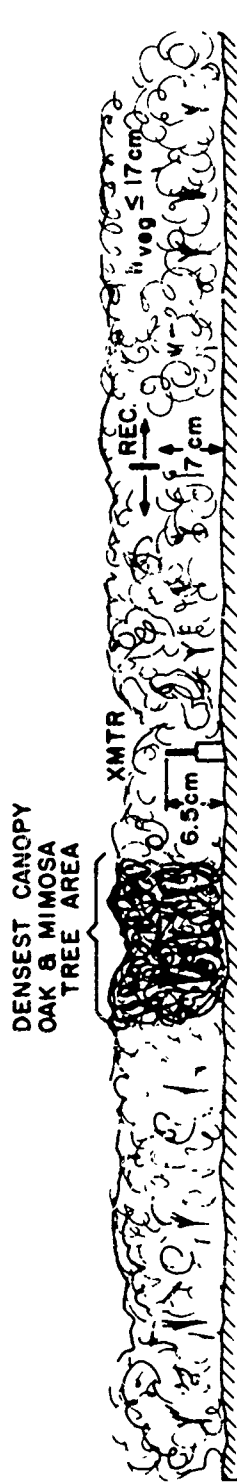


Fig. 16 JUNGLE MODEL: 6.5 GHz CW SIGNAL DECAY VERSUS DISTANCE BETWEEN XMTR - WHIP AND REC. WHIP IN VEGETATION. MARCH 30, 1971.

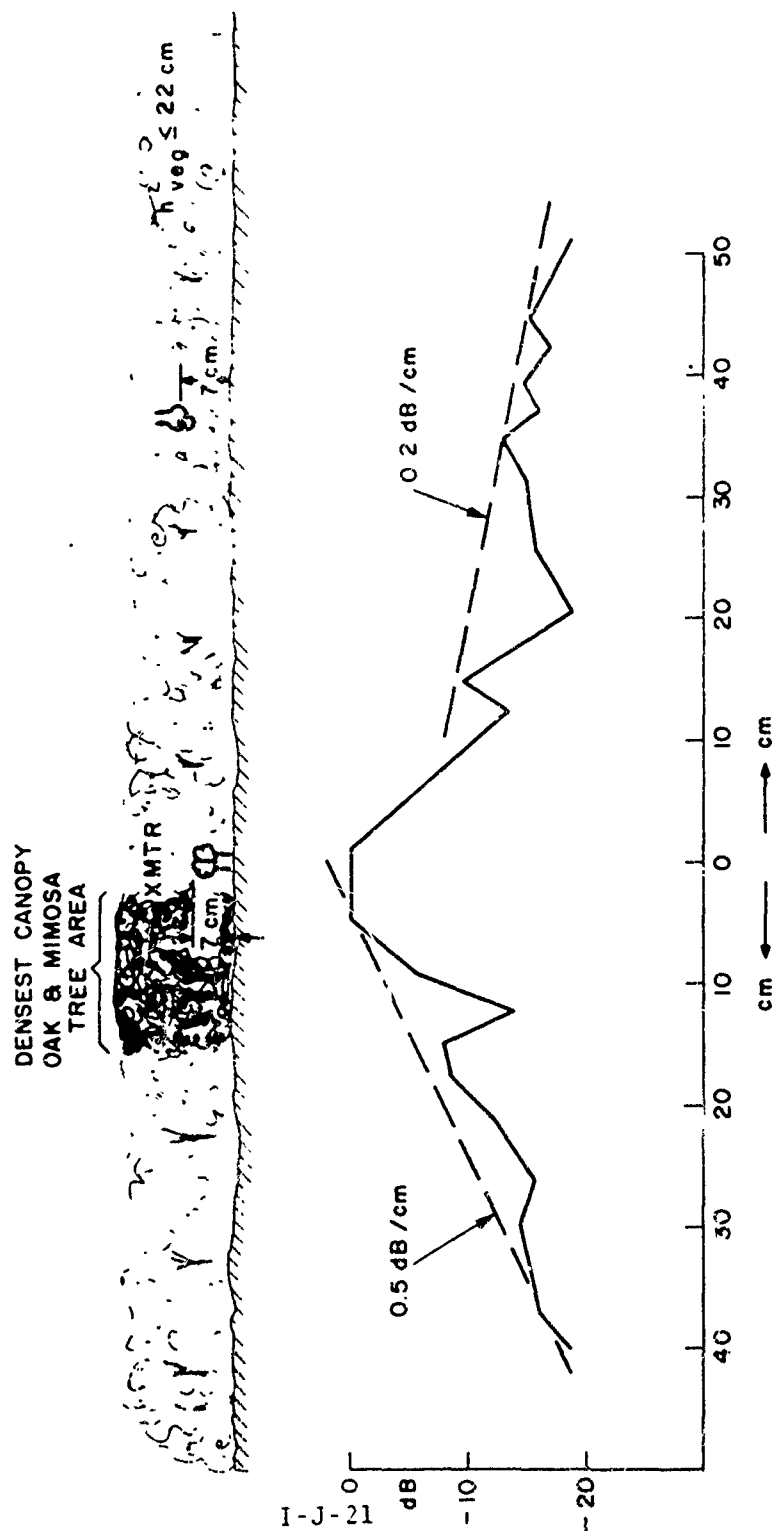
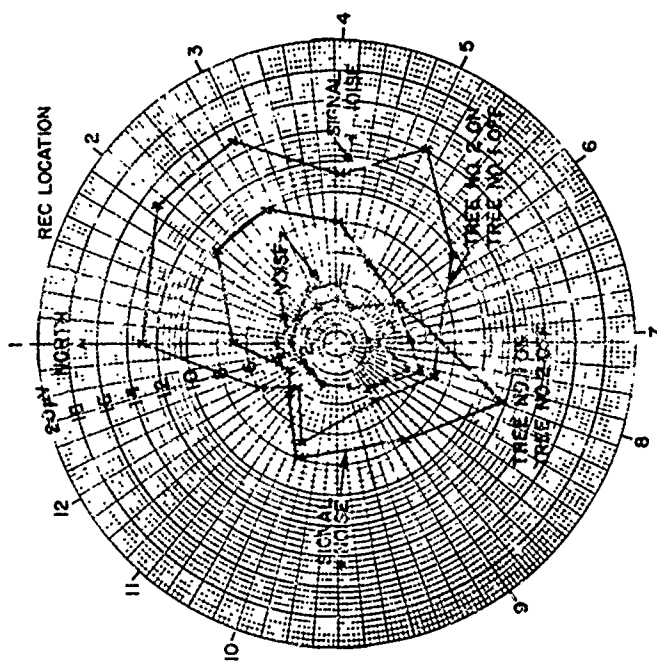


Fig. 17 JUNGLE MODEL 6.5 GHz CW SIGNAL DECAY VERSUS DISTANCE BETWEEN XMTR-HEMAC AND REC. HEMAC TOROID IN VEGETATION. MAY 4, 1971.



Fig.18 HSMAC Toroid Coupled Twin  
Array Wayide Test Area  
Sept., Oct. 1972



RADIATION PATTERNS OF HEMAC  
COUPLED TWIN FOREST-TREE XMTR ARRAY,  
WAYSIDE TEST AREA N.J. : FREQUENCY 4.650 MHz CW  
XMTR STATES:  
TREE #1 - ON = 1.15 AMP RF; TREE #2 - OFF  
TREE #1 - OFF; TREE #2 - ON = 1.15 AMP RF  
RECEIVER: B-K 2007 HETERODYNE VOLT-METER  
WITH 5 FOOT WHIP ON WEAPONS CARRIER  
XMTR - REC DISTANCE = 3 MILES  
MEASURED -- OCT 2 AND 3, 1972

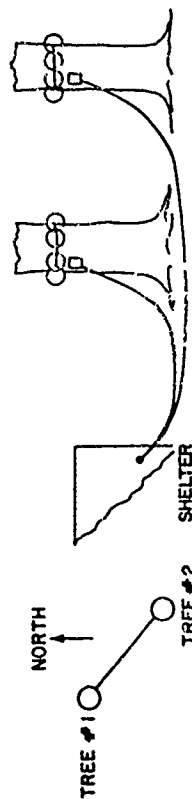
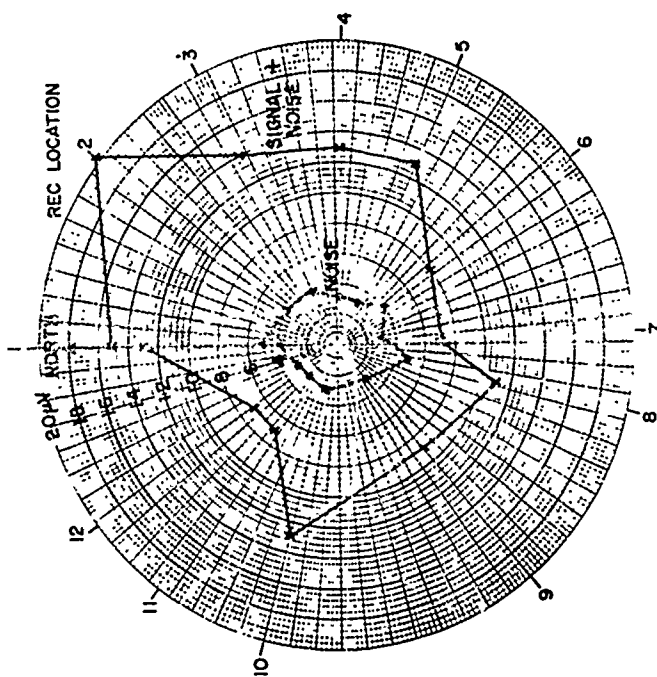


Fig. 19 Radiation Patterns of Hemac coupled Twin Forest Tree XMTR Array. (Tree #1 = on, Tree #2 = off, Tree #1 = off, Tree #2 = on)



RADIATION PATTERN OF HEMAC  
COUPLED TWIN FOREST - TREE XMTR ARRAY,  
WAYSIDE TEST AREA N.J.: FREQUENCY = 4.650 MHz CW  
XMTR - STATE:  
TREE #1 ON = 1.2 AMP RF ( $\approx 12$  WATT) AND  
TREE #2 ON = 1.2 AMP RF ( $\approx 16$  WATT)  
RECEIVER: B-K 2007 HETERODYNE VOLTMETER  
WITH 5 FOOT WHIP ON WEAPONS CARRIER  
XMTR - REC DISTANCE = 3 MILES  
MEASURED - OCT 2, 1972

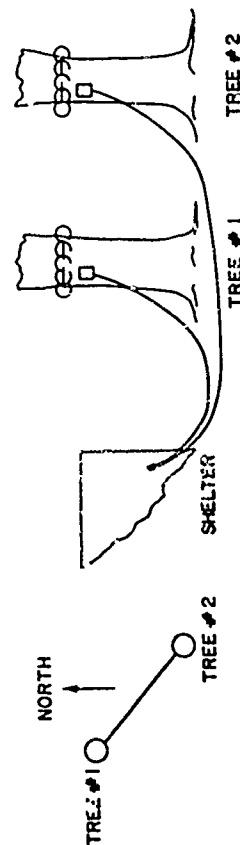
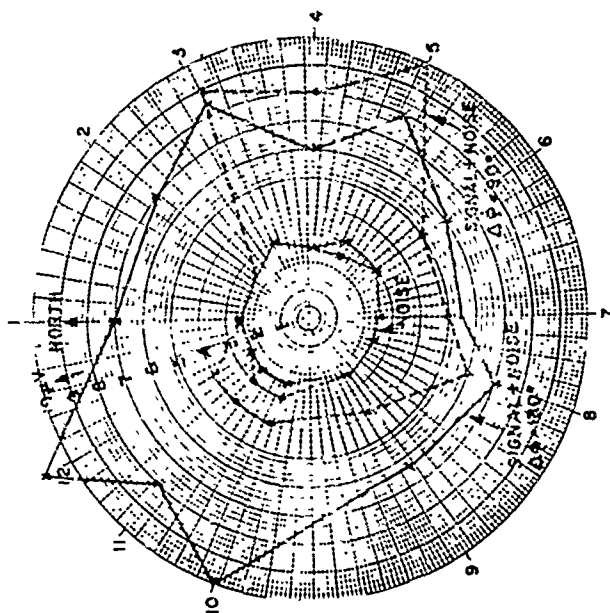


Fig. 20 Radiation pattern of Hemac coupled twin forest tree  
XMTR array (Tree #1 = on, and Tree #2 = on;  $\theta = 0^\circ$ )



RADIATION PATTERNS OF HEMAC  
COUPLED TWIN FOREST-TREE ARRAY,  
WAYSIDE TEST AREA N.1: FREQUENCY 1,650 MHz CW  
XMTR STATES:  
OCT 30/72 { TREE #1 ON=1.5 AMP RF AND  
Δφ=90° { TREE #2 ON=1.45 AMP RF  
OCT 18/72 { TREE #1 ON=1.3 AMP RF AND  
Δφ=180° { TREE #2 ON=1.3 AMP RF  
MAX AVAILABLE RF POWER FROM:  
XMTR #1=12 WATT, XMTR #2=16 WATT  
RECEIVER B-K 2007 HETERODYNE VOLTMETER  
WITH 5 FOOT WHIP ON WEAPONS CARRIER  
XMTR-REC DISTANCE=3 MILES

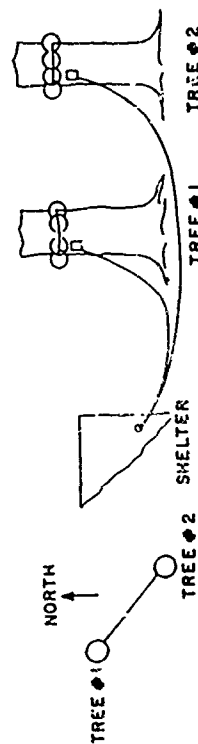


Fig.2] Radiation patterns of Hemac coupled Twin Forest Tree  
XMTR Array (Tree #1 = on and Tree #2 = on; =90°, 180°)  
Ft. Monmouth Area Oct. 1972

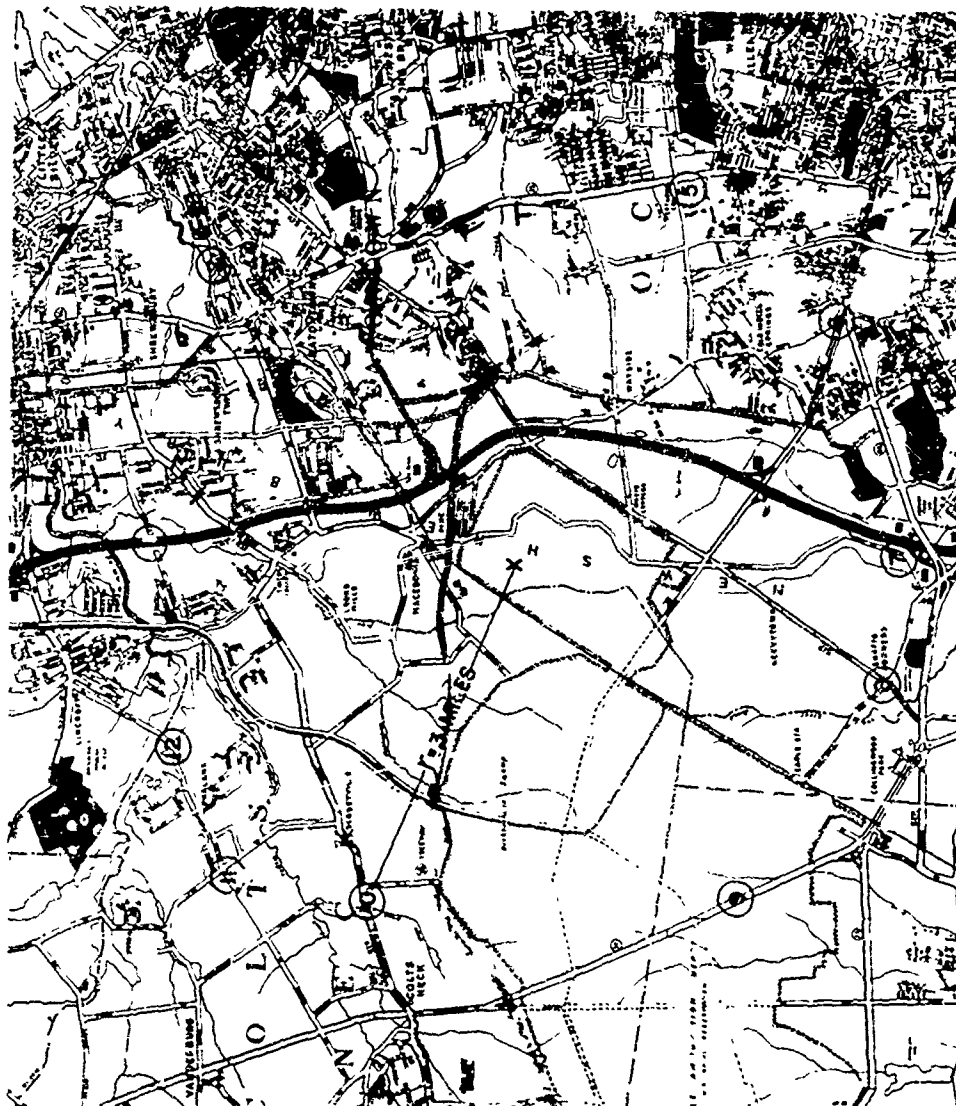


Fig. 22 MAP OF XMTR(X) AND RECEIVER LOCATIONS 1 TO 12  
MEASUREMENTS OF RADIATION PATTERNS FROM  
HEMAC COUPLED TWIN TREE XMTR ARRAY.

OCT. 1972

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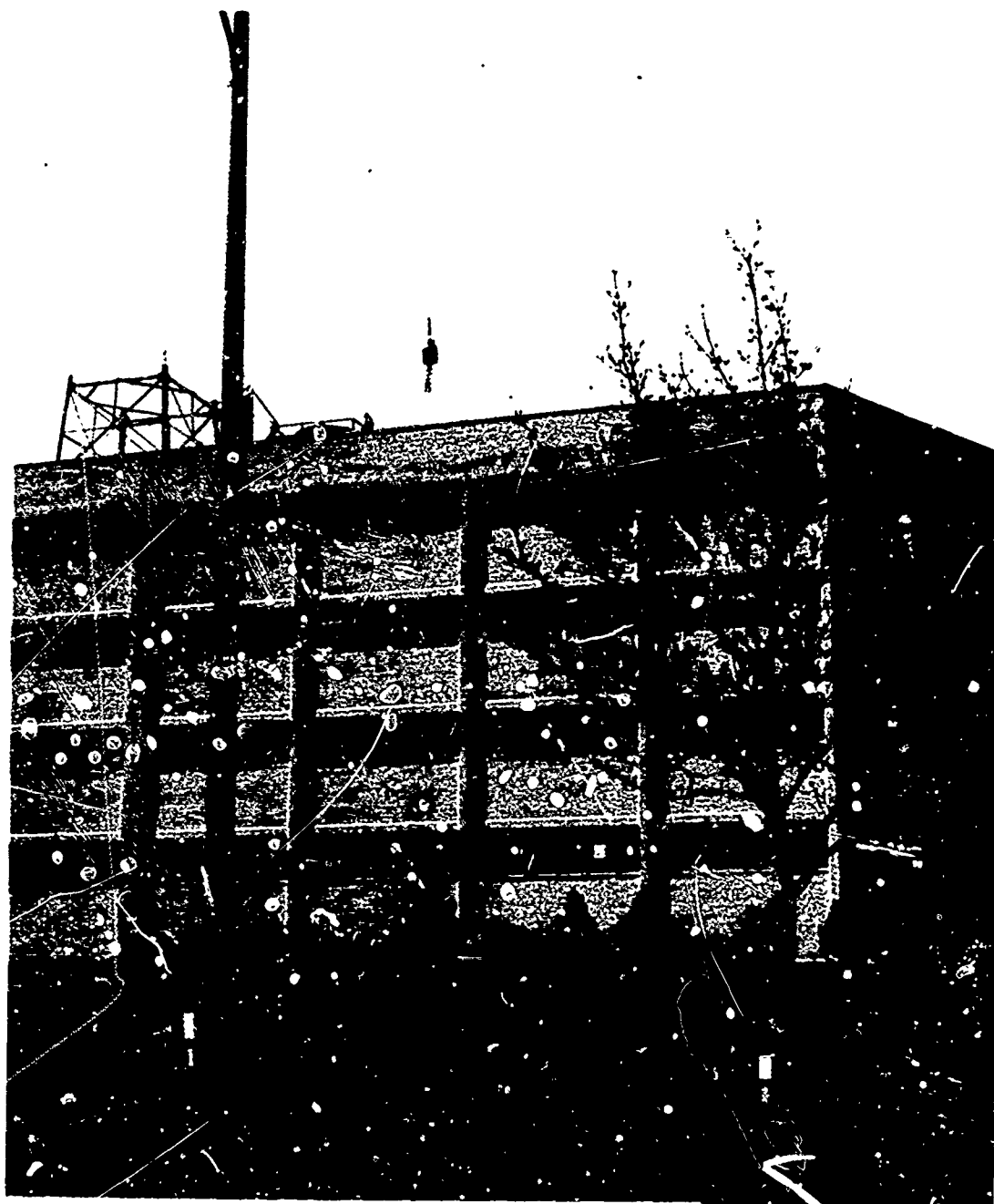
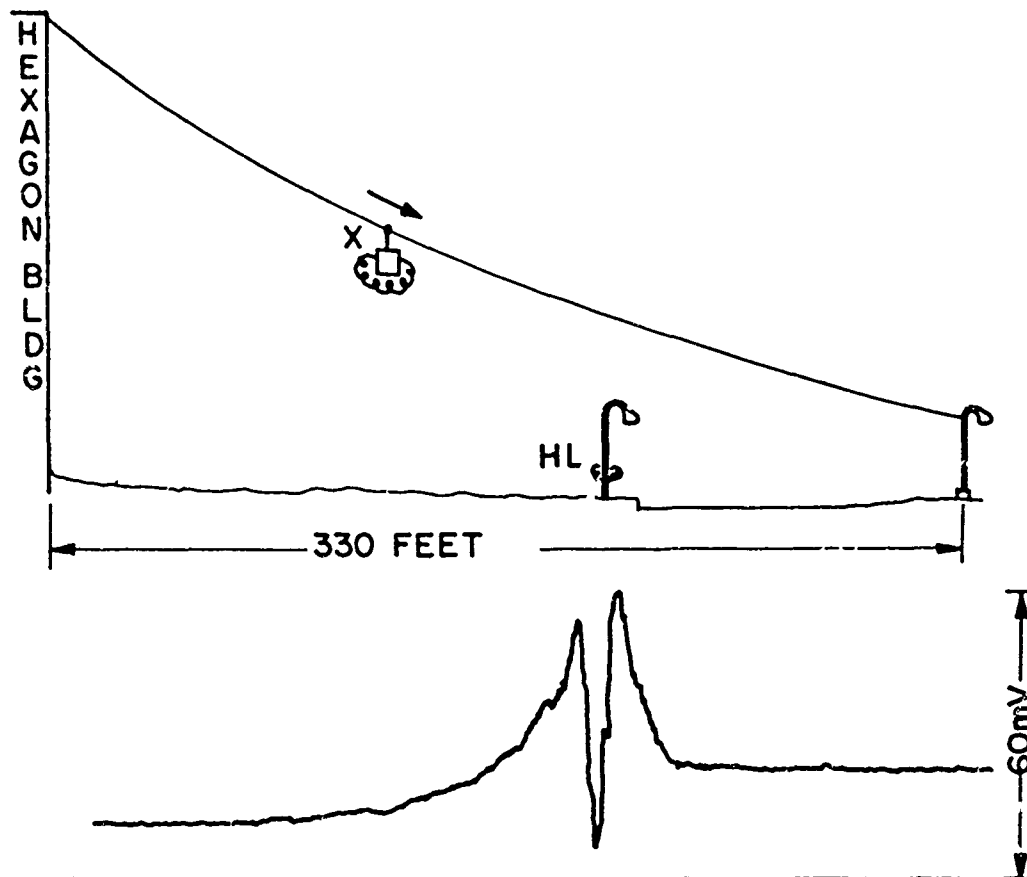


Fig.23 Aerial Tramway Gondola  
8.25 MHz XMTR above Tree and  
Lantern Pole Receiver Setup  
Hexagon Area • April 1973 I-J-27

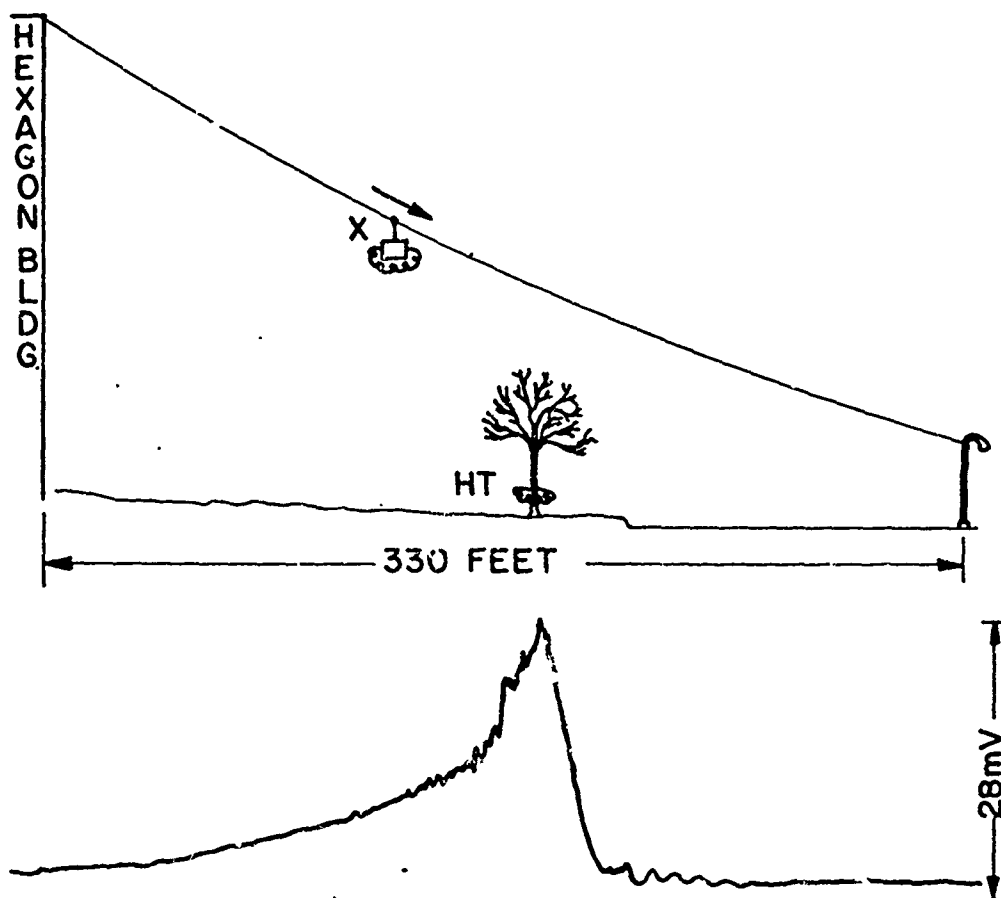


RECORDING OF 8.25 MHz OUTPUT VOLTAGE AMPLITUDE  
FROM HEMAC COUPLED LANTERN POLE (HL) VERSUS  
DOWN WARD MOVEMENT OF AERIAL TRAMWAY  
GONDOLA HEMAC XMTR (X)

APRIL 9, 1973

Fig.24

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RECORDING OF 8.25 MHz OUTPUT VOLTAGE AMPLITUDE  
FROM HEMAC COUPLED TREE (HT) VERSUS DOWNWARD  
MOVEMENT OF AERIAL TRAMWAY GONDOLA HEMAC  
XMTR(X)

APRIL 9, 1973

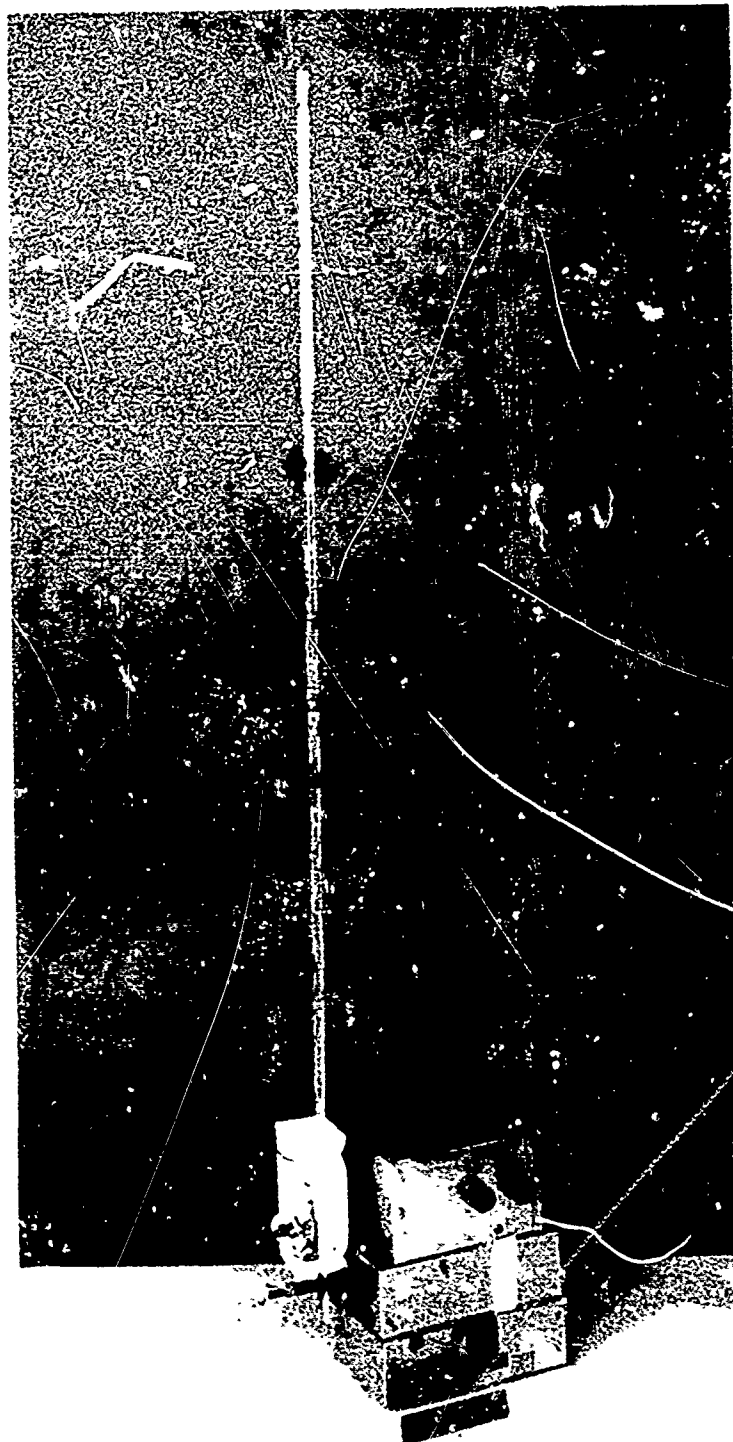
Fig.25

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Fig.26  
Body Coupled HEMAC-XMTR



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Fig.27 XMTR-Package with  
Reference Whip Antenna

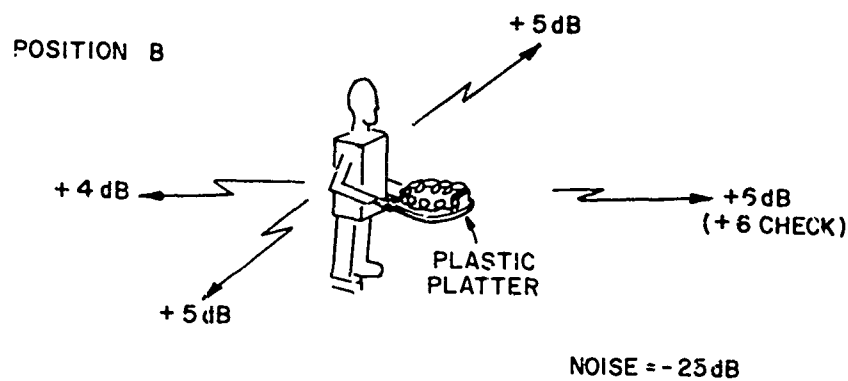
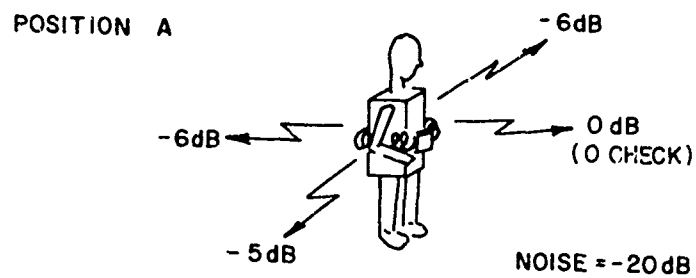


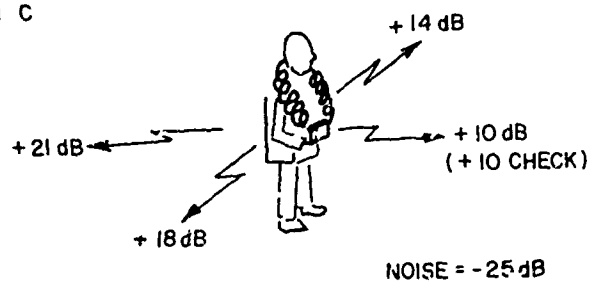
Fig. 4 (A and B). Relative Field-Strength Levels (dB) from Body Coupled 4.2-MHz Hemac XMTR, Wayside Test Area, 4 Dec. 1972.

Fig.28

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POSITION C



POSITION D

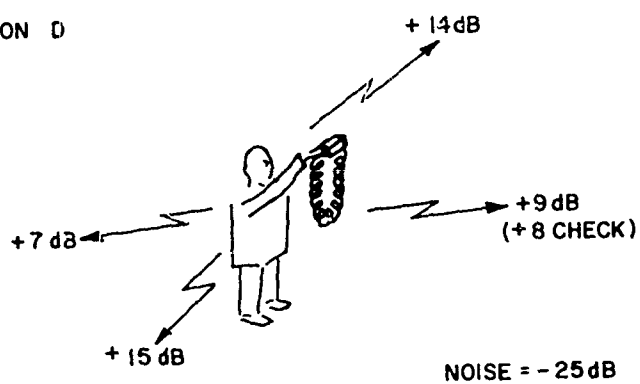
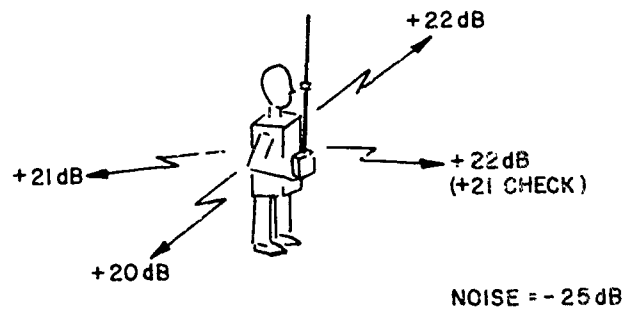


Fig. 4 (C and D). Relative Field-Strength Levels (dB) from body Coupled 4.2-MHz Hemac XMTR, Wayside Test Area, 4 Dec. 1972.

Fig. 20  
1-J-33 f.s.1

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POSITION E



POSITION F

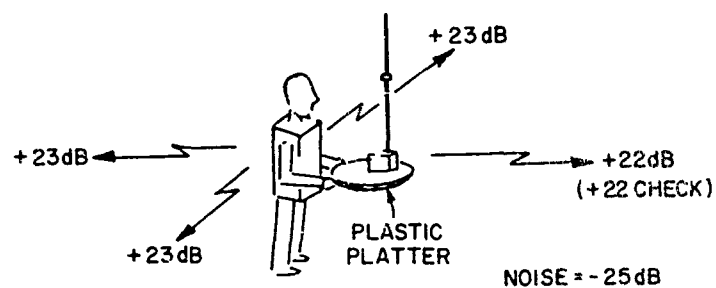


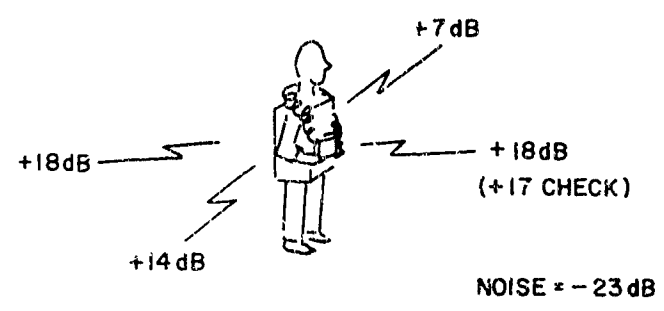
Fig. 4 (E and F). Relative Field-Strength Levels (dB) from 4.2-MHz Whip XMTR, Wayside Test Area, 4 Dec. 1972.

Fig.30

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POSITION G



Results: All levels for positions A to G measured with  
EMC-2 RFI-A and/or Field Strength Meter and  
with EMC-2 W. Antenna mounted on roof of  
vehicle, carrier, etc.

Fig. 4 (C). Relative Field-Strength Levels (dB) from Body Coupled  
4.2-MHz Hemac XMTR, Wayside Test Area, 4 Dec. 1972.

APPLIED MIXED-PATH THEORIES

by

Dr. James R. Wait

Office of Telecommunications  
Institute for Telecommunication Sciences  
Boulder Colorado 80302

Presented at

Workshop on Radio Systems  
in Forested and/or Vegetated Environments  
US Army Communications Command  
Fort Huachuca, Arizona

6-9 November 1973

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## APPLIED MIXED-PATH THEORIES

BY

Dr. James R. Wait\*

Abstract - We present a consolidated review of recent analytical studies of electromagnetic waves propagating over inhomogeneous surfaces. Emphasis is on smooth boundaries that can be characterized by a local surface impedance. A general integral equation formulation is developed for this situation. A number of special cases are then considered and various methods of solution are described. Various concrete, practical examples are presented, particularly with regard to effects that occur at coastlines. Extensions to certain types of terrain features are also treated using the closely related mode matching method. Some controversial aspects of very recent work on the subject are described briefly.

### INTRODUCTION

There are many problems in communications, navigation, and applied geophysics where the system performance is dependent on the electromagnetic ground wave. The latter refers to the wave that propagates along the surface of the earth such that its characteristics are influenced primarily by the profile and electrical properties of the earth's surface. Ten years ago, we reviewed the analytical aspects of this subject and attempted to give a self-contained account of the theory (1). Since then, there

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has been a large number of further developments that warrant mention. Also in view of new insight, a reappraisal of some of the older work is justified. In this context, we have prepared a review of the current work. Our attention is devoted mainly to the frequency ranges that are of relevance to navigation systems and communications. As such, the electrical properties of the surface layers are at least as important as the topographical features. Many of the methods should have application to radio wave transmission over forest covered ground. In this connection, we call attention to papers presented by Drs. T. Tamir and D. L. Sachs at this workshop.

Because of space limitations, we include here only the list of references upon which the review is based. Interested readers may obtain a copy of the full review from the author.

---

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Office of Telecommunications, Boulder, Colorado.

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EXCITATION MECHANISMS FOR TRANSMISSION THROUGH  
FOREST-COVERED AND VEGETATED MEDIA

by

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## I. INTRODUCTION

The propagation of a radio wave from a transmitter to a receiver, both located in a forest-covered or vegetated media (e.g., jungles), suffers the least attenuation along a ray-trajectory lying parallel to the interface between the top medium and air. This ray trajectory, called a lateral wave, is shown in fig. 1.

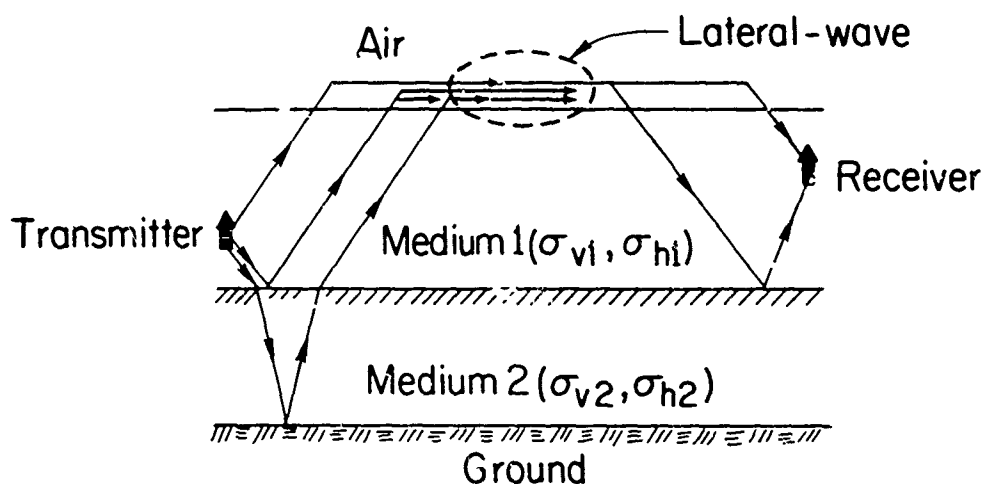


Figure 1. Geometry of transmitter, receiver, and lateral-wave

The lateral wave may suffer less attenuation than the direct ray (space-wave) or ground-reflected ray because a major portion of its path may be in air. One of the earliest measurements of attenuation by jungles was the work of Herbstreit and

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Crichlow (1964). Lippmann (1965) modeled Herbstreit's experiments in terms of a plane uniform slab. Jansky and Bailey Engineering Division (Jones and Sturgill, 1965), conducted a number of experiments in Thailand in 1965. Two of the earliest theoretical interpretations of the attenuation of signals propagating through a jungle are the work of Steinman and Tarr (1966) and Sachs (1966). Since then, a number of authors have considered the problem of calculating the lateral wave excited by antennas in a jungle (Tamir, 1967; Wait, 1967a, 1967b, 1968; Sachs and Wyatt, 1968; Dence and Tamir, 1969; Sachs, 1969). A very early treatment of lateral waves and their relation to other surface waves was the work of Tamir and Felsen (1964). Recently, models of the jungle vegetation have been built and model experiments have been conducted to complement actual field measurements (Ikraht and LeMarne, 1971).

In this paper we derive expressions for the lateral wave for a model of the foliage layer which can be as simple as a single homogeneous isotropic slab or as complicated as an arbitrary number of homogeneous, uniaxial anisotropic layers. In this analysis we ignore the incoherent or scattered-wave component. Also, the expressions for a lateral wave excited by a horizontal magnetic dipole (loop in the vertical plane) are derived. A comparison of the model with Jansky and Bailey data (1965) is given.

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## II. AN EXAMPLE

In fig. 2 we show the geometry and parameter values for two antennas located in a thick forest with dense foliage at the tree tops. Two homogeneous uniaxial-type anisotropic layers that could account (crudely) for the tree-trunk orientation are assumed. The upper foliage layer is isotropic, the lower tree-trunk layer anisotropic. The parameter values for the foliage and tree-trunk region are taken from Smith (1969). The model attempts to simulate the difference between the tree trunks and foliage. The transmitting and receiving antenna heights, together with the path length, were taken from Jansky and Bailey data.

In fig. 3, we show a comparison of theory, as described in this report, with a set of measured data selected at random. The predicted and measured basic transmission loss, defined as

$$\text{Basic Transmission Loss} = -20 \log_{10} |2E_z/E_o| + 20 \log_{10} (2k_o \rho) , \quad (1)$$

is plotted versus frequency in fig. 3. At 20 MHz, the predicted and measured values differ by about 3 dB. As the frequency increases above 20 MHz, the difference between theory and measured basic transmission increases to about 18 dB at 50 MHz. From 50 MHz to 300 MHz, the difference between theory and measured basic transmission loss remains constant and equal to about 18 dB. It is interesting that the theory predicts the

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greater loss, since the theory does not account for any extraneous losses. A possible explanation for the discrepancy between theory and measured data in fig. 3 may be that the measured data were taken with the receiving antenna located on a tower in a partial clearing. At low frequencies a partial clearing would be indistinguishable to the wave from the jungle itself. As the frequency is increased, the transition from jungle to clearing is more abrupt. As the frequency is increased still further, the loss will increase at a constant rate corresponding to one term in the residue series representation for the field strength,  $E_z$ . That is, for sufficiently high frequencies, and  $z = h = 0$

$$\frac{E_z}{E_0} \underset{f \rightarrow \infty}{\sim} \frac{1}{k_0 \rho |\Delta|^2} \quad (2)$$

In fig. 3,  $\rho$  is constant and equal to 1.609, and at sufficiently high frequencies,  $\Delta$  becomes

$$\Delta \underset{f \rightarrow \infty}{\sim} \frac{\sqrt{\epsilon_r - 1}}{\epsilon_r} \quad (3)$$

Substituting (2) into (1) gives

$$\text{Basic Transmission Loss} \underset{f \rightarrow \infty}{\sim} 40 \log_{10} f \quad (4)$$

which is shown as 40 dB/decade in fig. 3. It is encouraging that both theory and measured data obey the 40-dB loss per decade principle. The fact that both fall off at 40 dB/decade

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seems to indicate the validity of the slab model for jungle propagation.

Another possible explanation for the discrepancy between theoretical results and measured data shown in fig. 3 is the choice of constitutive parameters in fig. 2. It may be a different combination of these parameters would bring the theoretical results closer to the measured data in fig. 3.

As parameters for modeling a jungle and the effects of partial clearings are better understood, the slab model for making path loss predictions will become more useful.

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 [Note that  $\frac{\Lambda}{r_{||}}$  and  $\frac{\Lambda}{r_{\perp}}$ , as defined on p. 647, have a missing minus sign. Also, in equation (6), the plus sign between the two fractions within the braces (i.e., the fractions with exponential functions in the numerator) should be replaced with a minus sign. Also, delete the factor  $\lambda/u_0$  in (13) only.]
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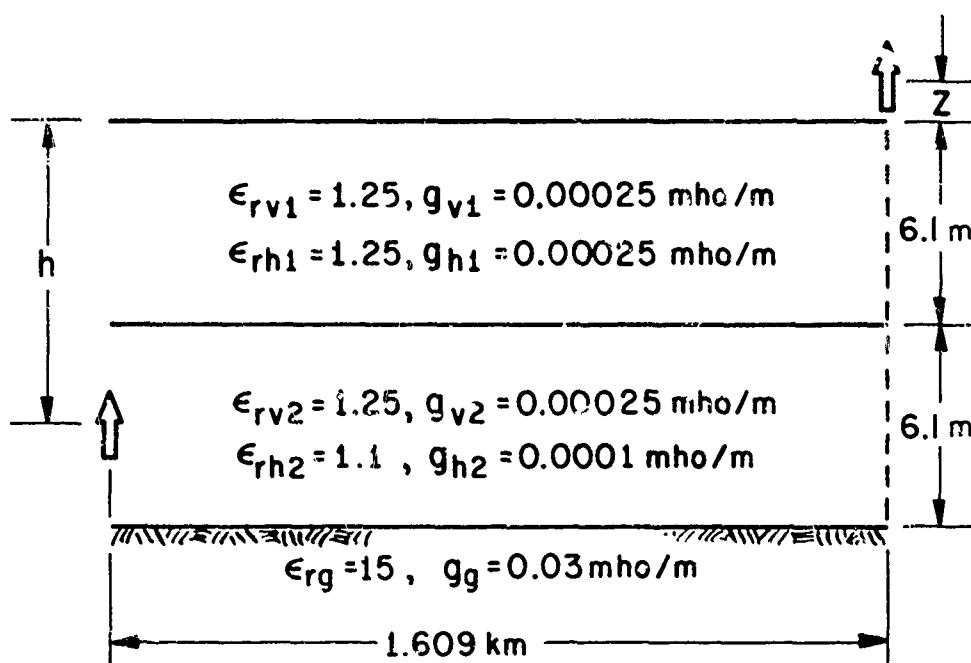


Figure 2. Geometry and parameter values for fig. 3.

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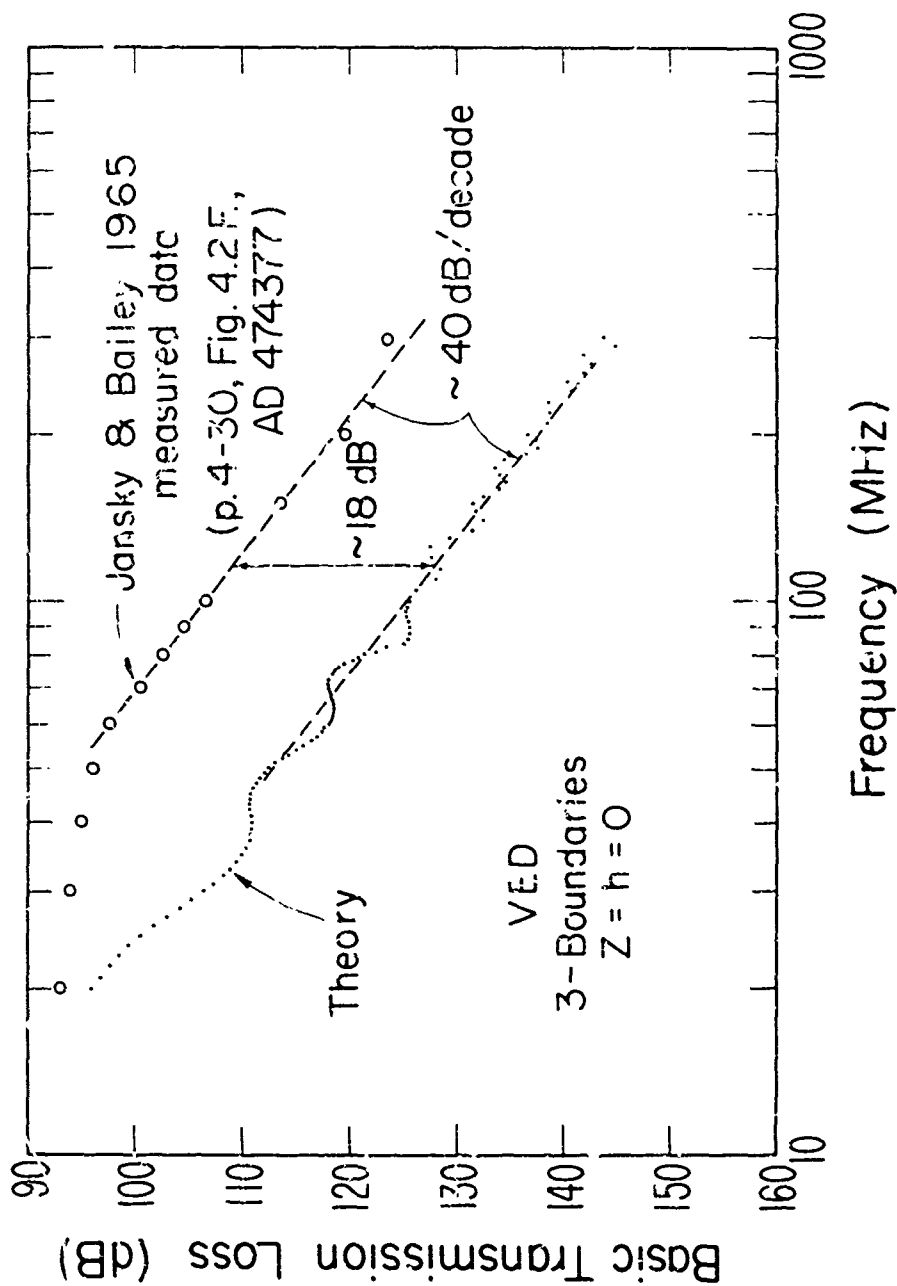


Figure 3. Basic transmission loss versus frequency for a VED and observer at the air-jungle interface.

TERRAIN EFFECTS ON PROPAGATION

by

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# TERRAIN EFFECTS ON PROPAGATION

by

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## I. INTRODUCTION

In general, techniques for predicting the effects of irregular inhomogeneous terrain on radio propagation fall into one of two classes:

- (1) theoretical, usually deterministic, formulations; and
- (2) empirical or semi-empirical statistical propagation models.

In an earlier paper at this meeting, Dr. Wait discussed one class of theoretical solutions involving paths whose terrain height and/or electrical characteristics change abruptly. In the first part of this paper, we show an integral equation for the attenuation function for a wave traveling over generalized irregular, inhomogeneous terrain; and show sample calculations of the effects for particular cases. In the second part of the paper, we describe the semi-empirical ITS model for predicting tropospheric transmission loss over irregular terrain.

## II. INTEGRAL EQUATION FOR PROPAGATION OVER IRREGULAR, INHOMOGENEOUS TERRAIN

Hufford (1952) originally developed a tractable integral equation for radio propagation over irregular terrain. The first numerical calculation of effects of smooth hills on propagation were made by Berry (1967). Ott (1971) derived the form of the equation that was used to compute the effects illustrated in this paper.

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The equation for the attenuation function,  $F(x)$ , relative to attenuation over a flat, perfectly conducting earth, is (Ott, 1971).

$$F(x) = W(x, 0, \Delta_r) - \sqrt{\frac{i}{\lambda}} \int_0^x F(s) e^{-ik\omega(x, s)} \left[ \frac{x}{s(x-s)} \right]^{1/2} \\ \cdot \left\{ \underbrace{y'(s) W(x, s, \Delta_r) - \left[ \frac{y(x) - y(s)}{x-s} \right] + (\Delta - \Delta_r) W(x, s, \Delta_r)}_{1} \right\} ds$$

where  $W(x, s, \Delta)$  is the Sommerfeld attenuation function for propagation from  $x$  to  $s$  over a flat earth with surface impedance  $\Delta$ ;

$y(x)$  is the terrain height at  $x$ ;

$\lambda$  is the radio wavelength and  $\kappa = 2\pi/\lambda$ .

$$\omega(x, s) = \frac{[y(x) - y(s)]^2}{2(x-s)} + \frac{y^2(s)}{2s} - \frac{y^2(x)}{2x} ;$$

$\Delta_r$  is the surface impedance at the transmitter, and  $\Delta = \Delta(s)$  is the variable surface impedance along the path.

The interesting thing about equation (1) is that the effects of terrain elevation variation and ground electrical constants (implicit in  $\Delta$ ) are separately displayed. The terms inside the brackets labeled "1" depend on the terrain elevation,  $y(x)$ . If the terrain is flat, and the same elevation as at the receiver, then both  $y'(s)$  and  $y(x) - y(s)$  are zero, and the equation simplifies to the integral equation for propagation over a path with varying surface impedance.

Similarly, the term labeled "2" contains the effects of variations in path electrical characteristics. If the surface impedance is constant

along the path, then the term labeled '2' is zero, so that for flat terrain of constant electrical constants, the integrand disappears, and we have the trivial result that F is the Sommerfeld attenuation function.

Ott (1971) has validated the computer program implementing (1) by showing that it computes the correct attenuation over a spherical, finitely-conducting earth, and that it reproduces the mixed path attenuation function for a smooth earth.

Calculations for ground wave propagation over a smooth, but prominent, hill show that the radio waves are focused on the front slope of the hill, producing field strengths as much as twice that possible over a perfectly conducting plane. On the other hand, there is a "shadow" on the back slope of the hill, and then a partial recovery far beyond the hill.

The importance of the terrain profile in mixed path problems can be illustrated by computing the attenuation function over an island, assuming first that the island is flat. This yields the familiar three-section, mixed-path result. Recalculation taking into account the island's elevation above sea level yields far different field strengths on the island itself; and a smaller, but appreciable, difference in field strength beyond the island.

The integral equation calculation can be used to solve practical antenna siting problems at HF. For example, an HF ground wave radar antenna was to be located on a beach with a ridge about 1500 m from the water. The question was, "Should the antenna be installed right at the water line to avoid the loss in propagating over the poorly conducting sand; or should it be located on top of the ridge to achieve height gain?" Calculations using the integral equation showed that the optimum location was part-way up the ridge's slope, where focusing by

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the slope increased the field strength over the sea by about 4 dB above that produced by an antenna right at the water's edge.

So far, the integral equation has been used to analyze propagation over irregular, inhomogeneous terrain at frequencies from 100 kHz (Loran) to HF. There is no reason that it cannot be adapted to compute attenuation over hilly inhomogeneous jungle terrain.

### III. THE LONGLEY-RICE MODEL OF RADIO PROPAGATION

The second approach to terrain effects is the empirical one. Here real life measurements are made the rule of the day. One says that here are the data and if you plan a system operating under similar conditions then this is what you should expect. The joker, of course, is the requirement for "similar conditions." Not only do systems seldom operate under conditions that appear similar, but one does not even know how to interpret the word "similar." A proper, universal, approach must be only semi-empirical. It must collate all of the data even though taken under a variety of conditions. And for the necessary interpolation and extrapolation to new conditions it must rely heavily on whatever theory is available.

One reason to abandon attempts at theoretical predictions, at least for frequencies at VHF and above, is obtained from a first cursory look at empirical data. The property that immediately strikes the eye is the large variability involved. Under seemingly identical conditions two measurements can differ by 20dB or more. Even if transmitting and receiving antennas are kept fixed, measured fields will vary in time because of often undetectable changes in the atmosphere and in the ground conditions. In the mobile situation a change of only a few feet in one of the antennas can produce a very large change in the received field.

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Under these circumstances it is not correct to tell the systems designer what the received field will be. One must tell him only what it is likely to be. One must, in short, provide a statistical description — one which gives not only the average field to be expected but also how much above and below that average the field is likely to go.

One such description developed at ITS has come to be known as the Longley-Rice (1968) Model of Radio Propagation. It covers the frequency range from 20 MHz to 20GHz. It is a semi-empirical model and is a judicious mixture of elementary theory, which defines possible extremes for the fields, and empirical formulas which interpolate between those extremes.

The necessary input parameters are fairly small in number. They consist of the system parameters such as frequency, distance, and antennas heights, of the radio meteorological climate including the minimum mean surface refractivity, of the ground constants and of a single parameter which characterizes in a rough way how irregular the terrain is. This parameter  $\Delta h$  is sometimes called the terrain irregularity factor. It is essentially equal to the interdecile range of terrain elevations.

The body of data upon which the model is based is very extensive and covers a wide range of conditions. And the results obtained from the model seem entirely consistent with this data. I think it fair to say that this model is unique amongst both theoretical and empirical models in the range of conditions for which it is valid.

But this is not to say that it covers everything. Indeed we like to think that the model is in a continuous state of development in which its accuracy is being improved and in which its range of applicability is being extended. Recently, for example, it has been extended to include

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ground wave effects and so covers much lower frequencies at short distances. Presently, we are engaged in a project which will try to extend the model to allow one or both antennas to be right on the ground.

Other areas that the model does not cover include propagation in urban environments and in forests, two areas that seem important to us. Surprisingly, we have in our possession some valuable data taken in forested mountains. It has been reported upon only in summary form (Barsis, 1971) and has never been analyzed in depth. We are hoping to have the time soon to examine it more closely.

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RADIATION PATTERNS OF SELECTED HF AND VHF ANTENNAS  
MEASURED IN OPEN AND FORESTED ENVIRONMENTS

by

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RADIATION PATTERNS OF SELECTED HF AND VHF ANTENNAS  
MEASURED IN OPEN AND FORESTED TERRAIN

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Abstract

Measurements of the radiation patterns of simple HF field-expedient antennas (dipoles, monopoles, inverted L's, slant wires, and loops) and vertical and horizontal VHF dipoles were conducted using an antenna pattern measurement system developed by Stanford Research Institute. The HF antennas were measured while situated over open (level) terrain, in a temperate pine forest, and in a tropical dry evergreen forest. The VHF antennas were measured while situated in a eucalyptus grove and in a tropical dry evergreen forest. This paper summarizes the major results obtained from the measurements of the dipoles and monopoles at each site, and intersite comparisons are made.

Introduction

Under the Southeast Asia Communications Research (SEACORE) Program, Stanford Research Institute (SRI) measured the radiation patterns of a number of field antennas located in simulated operational environments. These measurements were performed with the SRI-developed Xeledop\* antenna measurement system.

The Xeledop system has been described in detail in open literature<sup>1,2</sup> and SEACORE project reports<sup>3-9</sup> and it will be only briefly described here. The measurement system employs (but not simultaneously) two aircraft-towed

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\* Xeledop is an acronym for Xmitting (transmitting) elementary dipole with optional ppolarization.

multifrequency transmitters (approximating Hertzian dipoles), special purpose aircraft tracking and guidance equipment, and calibrated receiving and recording equipment, as shown in Figures 1 and 2, to measure the receiving patterns of antennas. (Reciprocity is assumed when measuring the patterns of transmitting antennas.) Two flight patterns and data processing techniques are employed: (1) two sets of orbits are flown at several elevation angles around the antenna to measure its horizontal and vertical polarization response, and (2) a grid of linear passes is flown above the antenna to determine its "power" response near the zenith. The data from these measurements are processed on digital computers and displayed as azimuthal equal-area projections of the measured antenna patterns.

#### Measurement Sites

The antenna pattern measurements were performed at four sites--three of these sites were in California and the fourth was in Thailand. (See Table 1.)

High frequency (HF) measurements were performed over open, level or gently rolling terrain near Lodi, California.<sup>3</sup> There were no terrain obstructions higher than a degree or two in elevation relative to the test site for at least a half mile in all directions.

HF measurements were performed in a pine tree farm located near Almanor in Northern California.<sup>4</sup> The trees, varying in height from 50 to 100 feet and in diameter from 1 to 13 feet, were randomly spaced approximately 10 feet apart. Undergrowth was sparse pine saplings. The antennas were erected in open spaces in the forest at least 200 feet from a small clearing used for the receiving van.

Initial VHF antenna pattern measurements were performed in a eucalyptus grove near Newark, California.<sup>5</sup> The average height of the mature trees was approximately 75 feet.

Both HF and VHF pattern measurements were performed in a tropical forest approximately 90 km southeast of Bangkok near the village of Ban Mun Chit, Thailand.<sup>6 7</sup> This gently rolling hill country was originally heavily forested but much of the forest has been removed for commercial and agricultural purposes. The forested area consisted of second growth. The equipment was situated in a clear area free of undergrowth adjacent to a moderately dense forest with an uneven, broken canopy. Tree heights were estimated to be 50 to 70 feet. Considerable undergrowth reached to a height of 20 to 25 feet. The ground was sandy and dry with good drainage; little standing water remained after heavy rains.

#### Measurement Antennas

Six types of antennas were measured at HF and two types at VHF. At HF,  $\lambda/4$  monopoles, balanced and unbalanced  $\lambda/2$  dipoles, 2:1 and 5:1 inverted-L's, 30-degree and 60-degree slant wires, sleeve dipoles, and a loop antenna were measured. Simplified diagrams of these antennas are shown in Figure 3. The HF antennas were measured at their resonant frequency. At VHF, only balanced and unbalanced horizontal  $\lambda/2$  dipoles and  $\lambda/2$  vertical sleeve dipoles were measured. The VHF antennas were measured only at their resonant frequency.

#### Measurement Results

The first HF measurements, performed in open terrain, showed that physical simplicity in antenna design does not imply electrical simplicity of the antenna. When the HF antennas were measured in the U.S. forest, significant changes were noted in the radiation patterns of the antennas measured above 8 MHz. The  $E_0$  (vertical polarization) pattern of the monopole antenna was omnidirectional up to 5 MHz (the maximum measurement frequency) in open terrain, but the azimuthal pattern became quite broken when measured at, and above, 8 MHz in the pine forest. When the antenna was measured in the Thailand tropical forest, it was observed that the omnidirectional pattern of the antenna started to deteriorate

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for measurements at 6 and 8 MHz, but not as significantly as when measured at the U.S. Forest site. The 6 MHz patterns of this antenna at the three sites is shown in Figure 4. It is also worth noting that the elevation angle of the maximum gain increased when the antenna was measured at the forested sites.

Measurements were performed on an 8 MHz,  $\lambda/2$  unbalanced dipole antenna at the three HF measurement sites. The classical dipole pattern was observed over the measured elevation angles (approximately 5 to 60 degrees) when the antenna was measured over open terrain and the maximum measured  $E_\phi$  (horizontal polarization) and  $E_\theta$  (vertical polarization) components were almost equal ( $E_\phi/E_\theta = 0.5$  dB).<sup>\*</sup> The most significant change observed in the patterns of this antenna when measured at the forested sites is that the gain at low elevation angles was greater (relative to the maximum observed gain) than when the antenna was measured at the open site (see Figure 5), and this was true for both polarizations, although more noticeable for the  $E_\phi$  response. Figure 6 shows that this phenomenon has been validated by mathematical models of dipole antennas in vegetation.<sup>8,9,10</sup> Similar results were observed for a 6 MHz dipole antenna measured in the forest and a cleared area at the Thailand field site.

At VHF, the effects of the forests on the antenna radiation patterns became more pronounced. Preliminary measurements of VHF antenna patterns were made in the Newark eucalyptus grove at 50, 75, and 100 MHz primarily to verify the operation of the then newly developed VHF Xeledop system. These measurements showed significant pattern perturbations to the  $E_\theta$  patterns of vertical sleeve dipole and less significant disturbance to the  $E_\phi$  response of horizontal dipoles. (Examples are shown in Figure 7.) This pronounced perturbation of the  $E_\theta$  patterns would be expected since

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\* Note that the maximum  $E_\phi$  response is broadside to the antenna and the maximum  $E_\theta$  response is off the ends of the antenna elements. The ratio of the maximum  $E_\phi$  and  $E_\theta$  components is independent of the location of these measured values.

the grove was composed primarily of vertical tree trunks. The pronounced variability of the received signal strength as a function of azimuth angle observed in these measurements indicated that statistical techniques would be required to interpret and understand the effects of vegetation on VHF antennas.

The data resulting from the VHF measurements performed in the tropical forest in Thailand were processed statistically to derive contour plots of the median measured signal strength,  $\hat{\mu}$ , and to estimate the standard deviation,  $\hat{\sigma}$ , about these medians.\* To evaluate the repeatability of the results the patterns of one of the antennas were measured twice, on different days. The resulting patterns from the two measurements appeared identical, and the maximum median gains were within 0.7 dB of each other for  $E_0$  and 0.5 dB for each other for  $E_\theta$ .

Measurements of vertical sleeve dipoles were conducted when the antennas were located in the forest and in the clearing. The median response of the antennas shows significant perturbations to the pattern (see 100 MHz pattern of a sleeve dipole in Figure 8). An estimated standard deviation of 2 to 3 dB must also be added to the pattern shown in the figure. When horizontal dipole antennas were measured in the tropical forest, the median pattern was characteristic of that of a dipole antenna (see 100 MHz pattern in Figure 9). The lobes of the dipole antennas tended to occur at higher elevation angles than when the same antenna was located in the clearing. Generally, the standard deviation was greater for  $E_\theta$  than for  $E_0$  for a given antenna, and the standard deviation of the  $E_\theta$  response increased when the antenna was moved from the clearing to the forest while the standard deviation of the  $E_0$  response decreased. Generally, there was not a significant increase in the standard deviation as the measurement frequency increased from 50 to 100 MHz.

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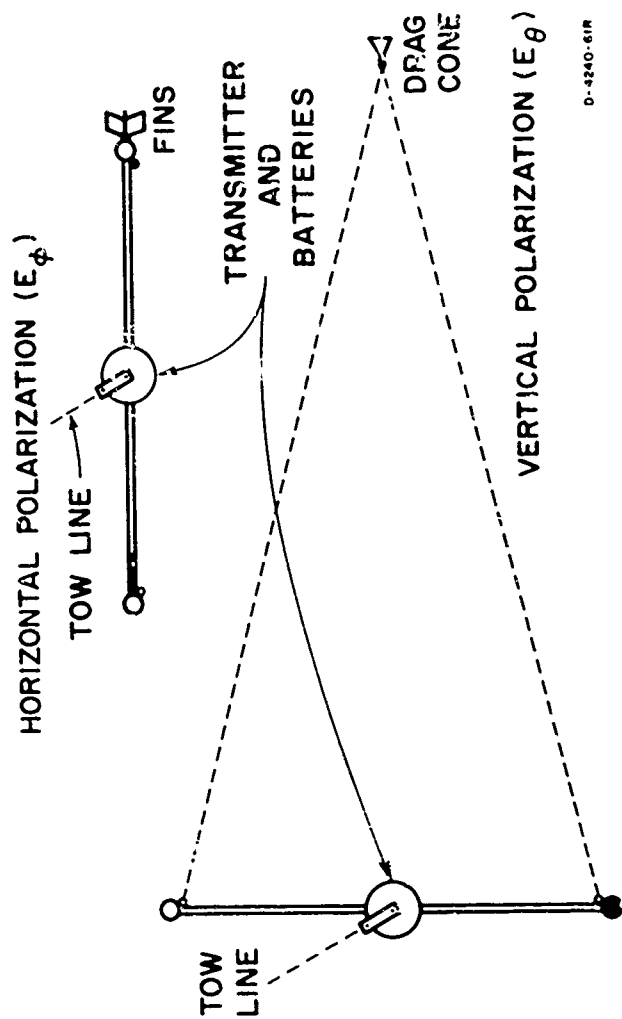
\*  $\hat{\mu}$  and  $\hat{\sigma}$  were calculated over 10-degree azimuth sectors of the data resulting from the measurement orbits.

### Summary

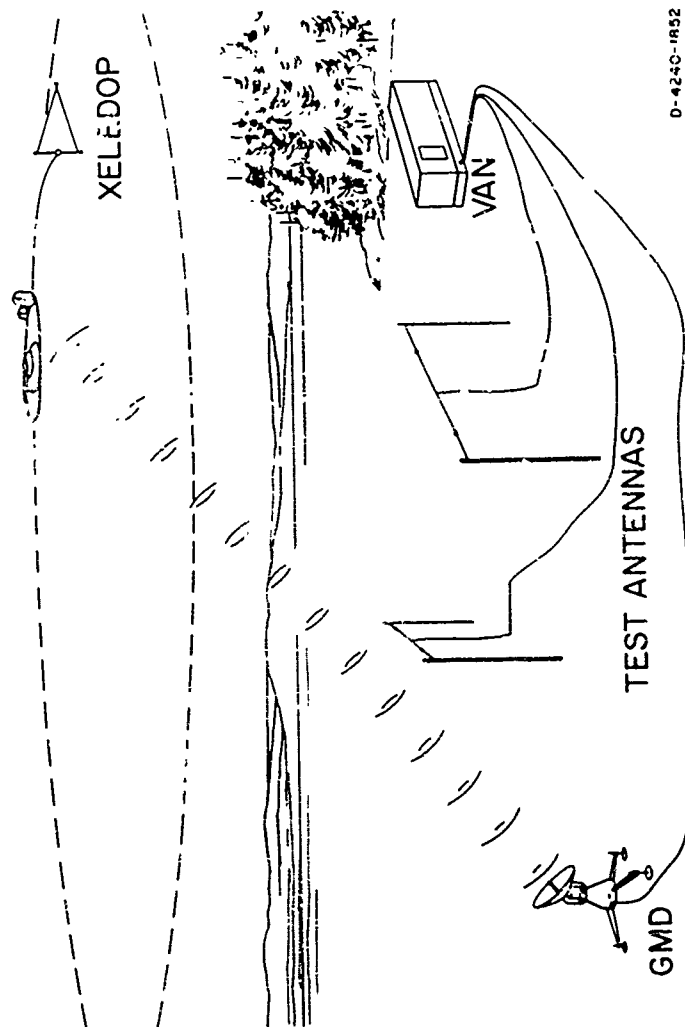
The Xeledop antenna pattern measurement system has proven to be a valuable aid in determining and understanding the operation of simple antennas in forested environments. The use of the Xeledop has allowed better documentation of mathematical models and led to techniques to acquire and consolidate large quantities of antenna pattern information into meaningful forms. It is recommended that, if further work is conducted in this area, further data be obtained to establish statistical parameters for models of antennas in forest environments.

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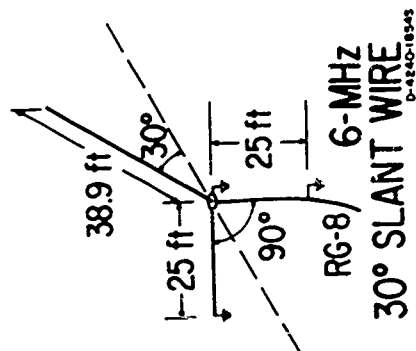
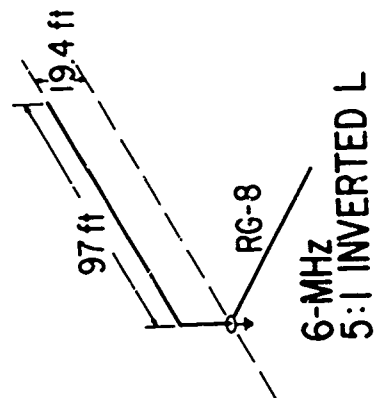
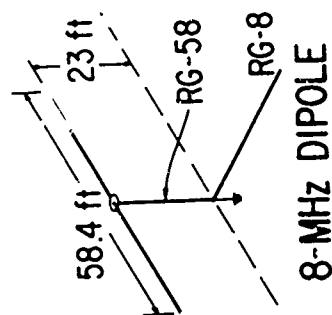
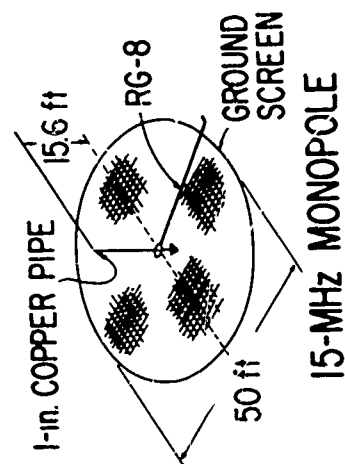
D-4240-61R



D-4240-1852

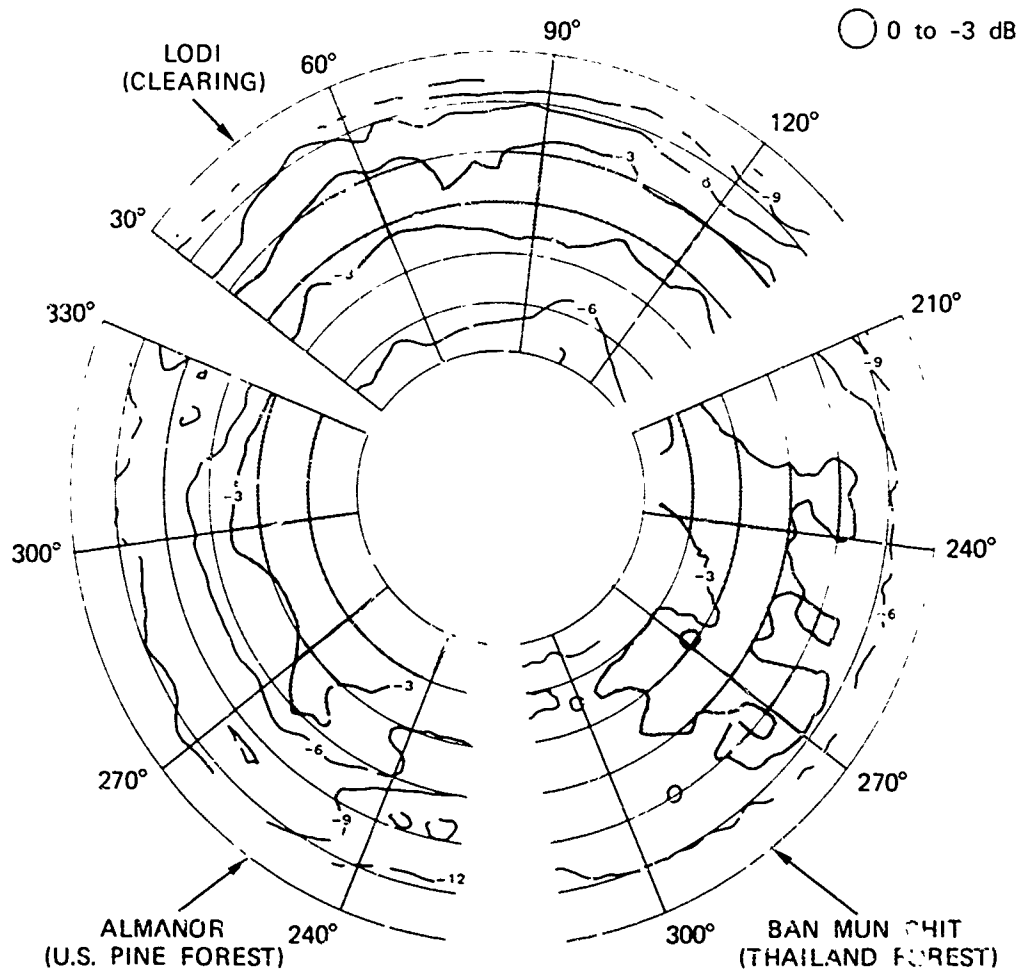
# ANTENNA MEASUREMENT SITES

Site	Measurement Frequency Band	Forest Type	Tree Height	Undergrowth
Lodi, California (open terrain)	HF	None	0	None
Almanor, California (U.S. forest)	HF	Pine	50 to 100 ft	Saplings
Newark, California (eucalyptus grove)	VHF	Eucalyptus	75 ft	Poison oak
Ban Mun Chit, Thailand (tropical forest)	HF VHF	Dry evergreen	50 to 70 ft	Dense vines to 20- or 25-foot-height



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MONOPOLE ANTENNA,  $E_\theta$  AT 6 MHz

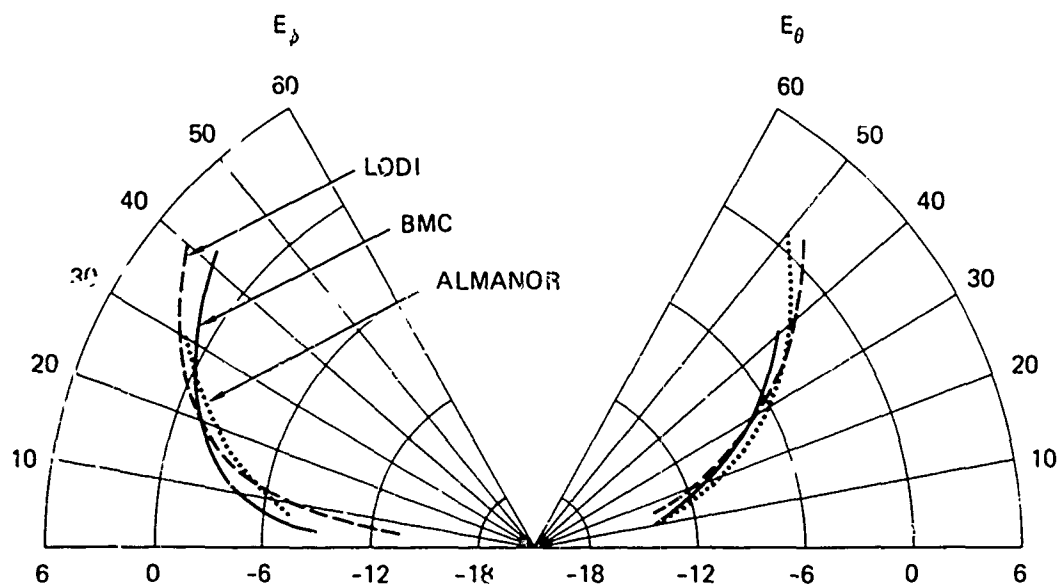


TA-8663-114R

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# 8 MHz HORIZONTAL DIPOLE



TA-810524-1

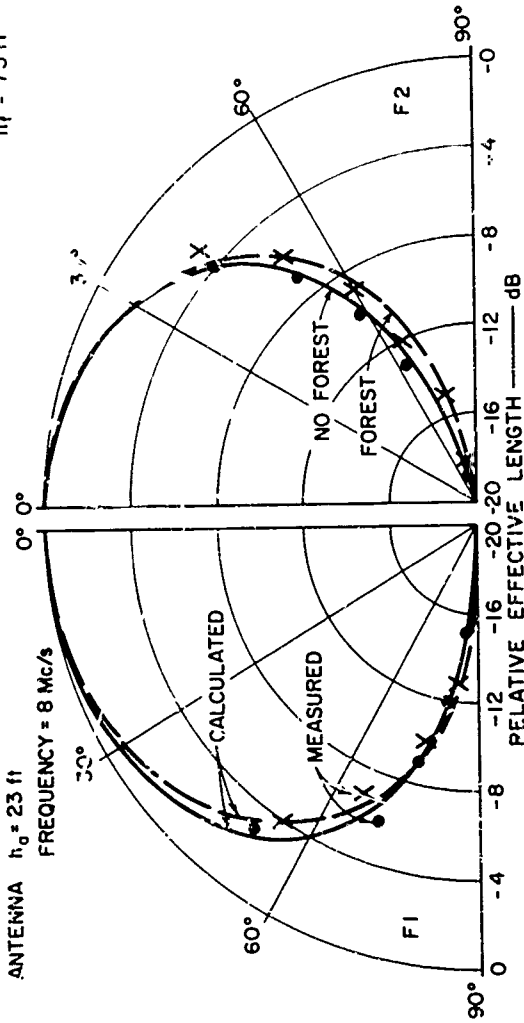
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FOREST  $\epsilon_{r1} = 1.2$   
 $\delta_1 = 0.1$   
 $h_1 = 75 \text{ ft}$

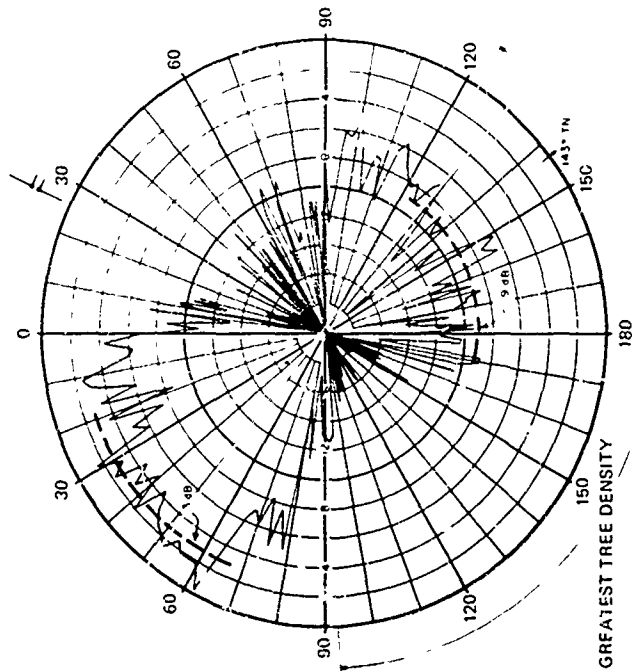
GROUND  $\epsilon_{r2} = 2.0$   
 $\delta_2 = 5$

ANTENNA  $h_a = 23 \text{ ft}$   
 FREQUENCY = 8 Mc/s



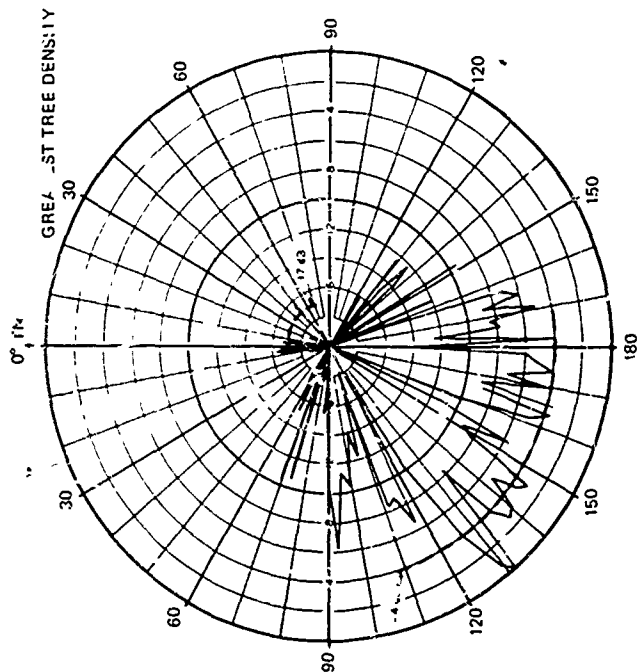
PATTERN IN PLANE  $\perp$  DIPOLE PATTERN IN PLANE OF DIPOLE 0-4240-630

100 MHZ HORIZONTAL DIPOLE IN EUCALYPTUS GROVE  $I_{\theta}$

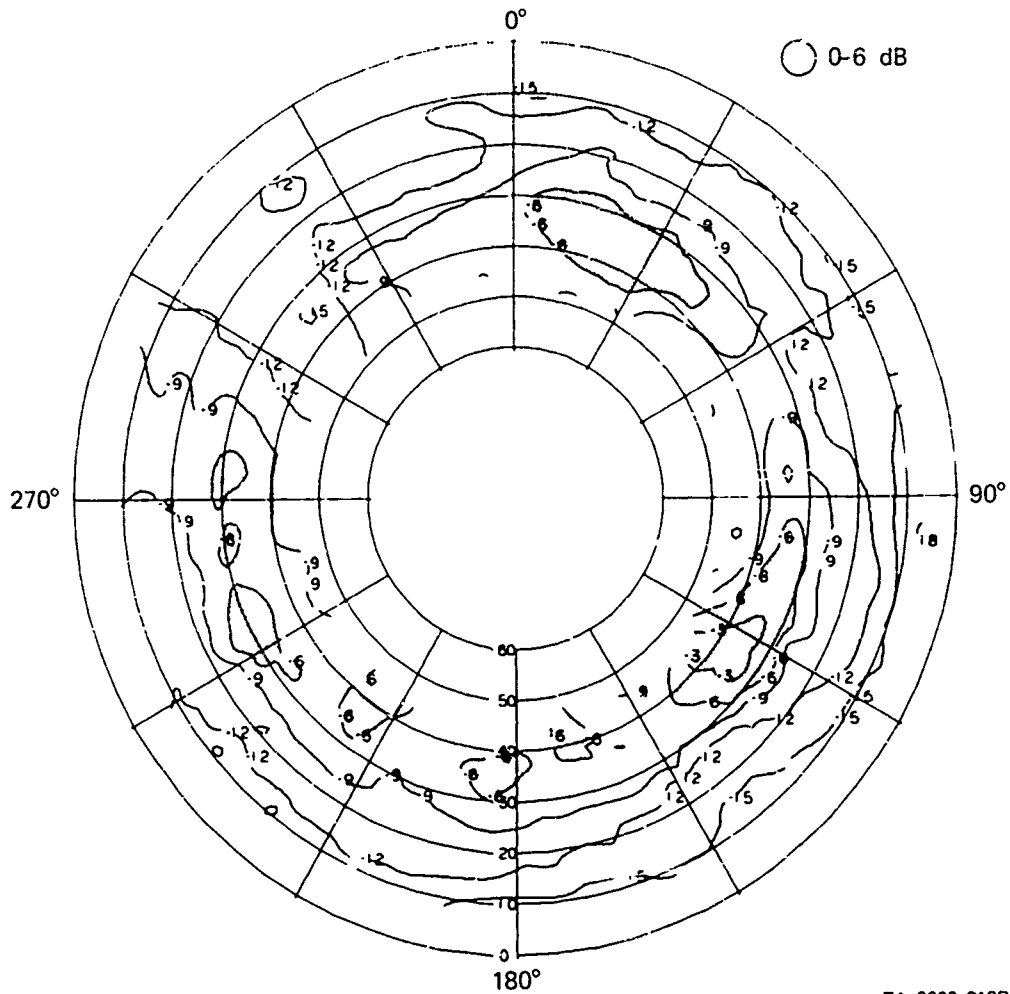


TA 810524-2

100 MHZ VERTICAL SLEEVE DIPOLE IN EUCALYPTUS GROVE  $E_{\theta}$

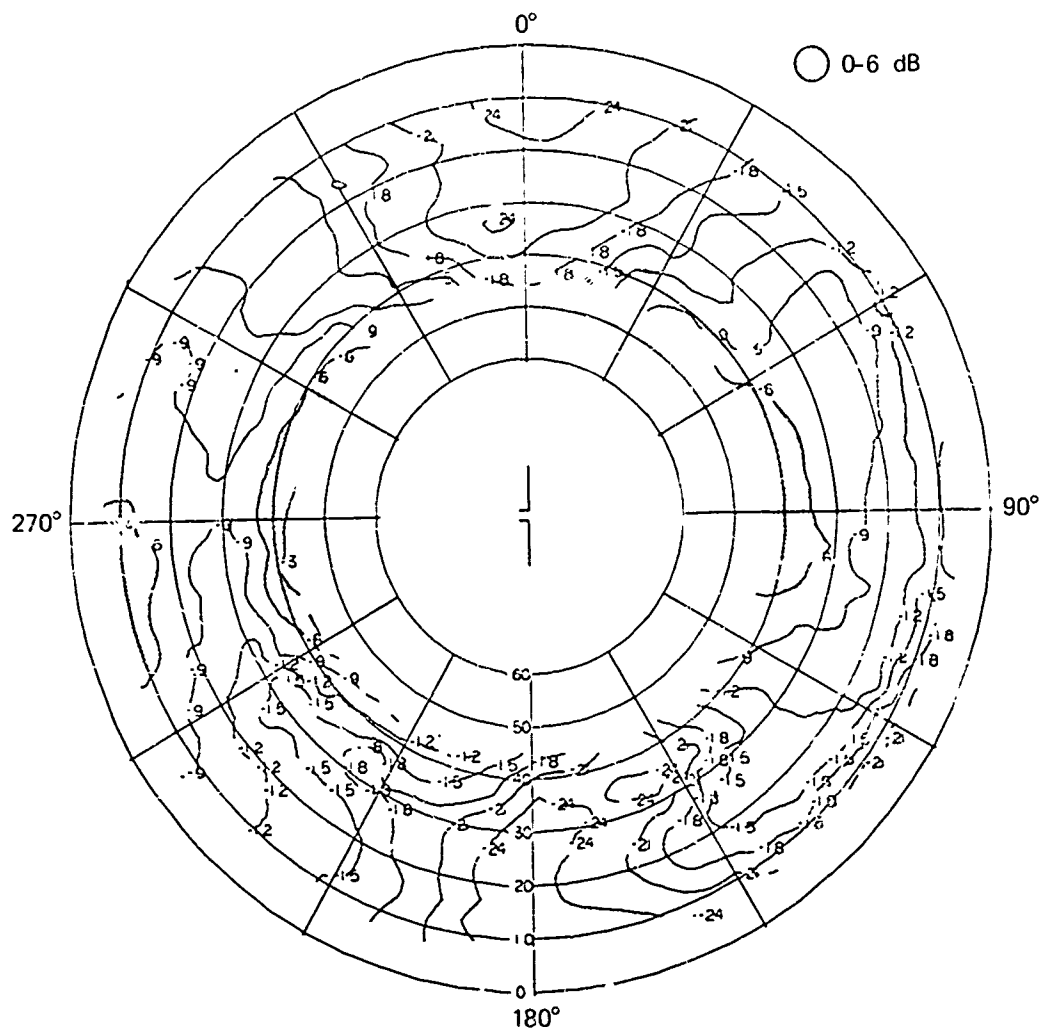


VERTICAL SLEEVE DIPOLE IN TROPICAL FOREST -  $E_\theta$  AT 100 MHz



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# HORIZONTAL DIPOLE IN TROPICAL FOREST - $E_{\phi}$ AT 100 MHZ



TA-8563-213R

ELECTRICAL CHARACTERISTICS OF EARTH MEDIUM

by

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Presented at

Workshop on Radio Systems  
in Forested and/or Vegetated Environments  
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## ELECTRICAL CHARACTERISTICS OF EARTH MEDIUM

A presentation of the Electromagnetics and Systems Research Group,  
Lawrence Livermore Laboratory. By R. Jeffrey Lytle

An overview of measurement techniques, measurement results, and factors influencing the conductivity and dielectric constant of earth medium is given. Application of these measurement techniques to geophysical investigations is also discussed.

### Acknowledgement:

Various members of the Lawrence Livermore Laboratory Electromagnetics and Systems Research Group have provided input in the preparation of this report. These members are E. F. Laine, D. L. Lager, E. K. Miller, and A. J. Poggio.

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## ELECTRICAL CHARACTERISTICS OF EARTH MEDIUM

### I. INTRODUCTION

The earth electrical conductivity  $\sigma$  and dielectric constant  $\epsilon$  can have a decided effect upon the performance of electromagnetic systems. These parameters influence the choice of antenna, the antenna efficiency, whether a ground screen is needed and its size, the transmission loss and phase shift, the dominant path of propagation, the effect of dispersion, hardening considerations, the relative communication efficiency, and environmental effects, among other factors. Values of  $\sigma$  and  $\epsilon$  for a wide number of environments are hence needed in theoretical assessments of system utility.

Examples of laboratory and in situ methods of determining  $\sigma$  and  $\epsilon$  are given in this paper. Some references describing the methods are given, however, the reference list is not to be considered definitive. There are numerous other references describing these procedures which are not listed herein. For general background information, a list of overview references (7-18) concerned with electrical probing of the earth (with particular emphasis on methods of measuring  $\sigma$  and  $\epsilon$  and results for  $\sigma$  and  $\epsilon$ ) are presented. A more detailed version of this summary and an expanded reference list is given elsewhere (18).

The electrical constitutive parameters  $\sigma$  and  $\epsilon$  depend upon frequency, water content, temperature, geological constituents, weathering factors, local anomalies, and other considerations. Due to the myriad factors influencing  $\sigma$  and  $\epsilon$ , it is preferable to perform in situ measurements of  $\sigma$  and  $\epsilon$ , rather than perform laboratory measurements on "representative samples" or to rely on "textbook values". Hence, in situ measurement schemes, rather than laboratory measurement schemes or "nominal values" for  $\sigma$  and  $\epsilon$  are stressed in this summary.

In situ measurement schemes have the potential of probing the near surface, as well as greater depths. These techniques thus can be used for detecting buried objects, faults, and discontinuities in addition to determining the ground parameters. For example, these methods have been used to determine the location of plastic and metallic pipes, the depth of the water table, the location of gravel deposits, identifying mineral nodule deposits on the ocean floor, determining glacial ice depth, defining geothermal areas mapping the boundaries of buried salt domes, and locating underground chambers. In many situations, large propagation losses or severe data inversion requirements preclude successfully determining a detailed subsurface profile of  $\sigma$  and  $\epsilon$ . Nevertheless, in situ measurement schemes and data inversion methods do hold great promise in geology, hydrology, mining, energy resource location and extent definition, and archaeology exploration, among others.

### II. LABORATORY MEASUREMENTS

#### A. Bridge Methods

A parallel-plate capacitor is commonly used to hold the right circular disc sample of the material. This method has been used for frequencies of  $10^{-2}$

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to  $10^{+9}$  Hz. Procedures exist for accounting for the inductance and conductance of the connecting leads. Much care has to be taken to insure a good contact between the sample and the electrodes. Substitution techniques with liquid immersion of the sample enable one to attain high accuracy for the loss tangent.

B. Transmission Line Methods

A short circuited transmission line with the sample at the end of the line enables one to use standard impedance transformation formulae to evaluate the propagation constant in the sample (which is related to the complex dielectric constant of the sample). Electrode-sample contact problems can be overcome.

C. Resonant Cavity Methods

A cavity resonator is convenient for dielectric measurements. Either disc or coaxial rod samples may be used. The analysis is based upon the impedance of the sample which is determined via the Q of the cavity, the dimensions of the cavity, and/or the cavity transmission coefficient.

D. Scattering and Transmission Methods

The complex refractive index can be determined from comparisons of the theoretical solution and experimental results for scattering from a spherical sample and transmission through a planar sample. Extensive theoretical results are available for these situations. Very accurate phase and amplitude measurements are required. It is necessary that the sample be penetrable (i.e., the transmission loss through the sample should be measurable). Non-unique solutions are possible but use of two different size samples can overcome this difficulty.

III. SURFACE MEASUREMENTS

A. Power Reflectivity

Determination of the reflection coefficient at the ground surface enables one to estimate  $\sigma$  and  $\epsilon$  of the ground. This method is also useful for a stratified medium with a low loss upper layer. Time of arrival measurements are helpful in determining the thickness of the upper layer, and attenuation measurements are helpful in evaluation of the conductivity of the upper layer. Surface roughness can invalidate this procedure.

B. Two Loop Method

Measurement of the mutual impedance between two loops above ground enables one to estimate  $\sigma$  and  $\epsilon$  of the ground.

Data interpretation curves (based upon Sommerfeld integrals) exist for homogeneous and vertically stratified grounds. Models include both conduction and displacement current effects. This mutual impedance procedure has been used for ELF to HF. This method has  $\sigma$  resolution problems when  $\omega\epsilon_0\epsilon_r \gg \sigma$ .

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### C. Wave Tilt Method

The tilt of an electromagnetic wave near the ground surface at a moderate distance from the transmitter is simply related to the local ground conditions.

The electric field vector traces out an ellipse as a function of time at the observation point. By measuring the major and minor axis of the ellipse, or the radial and vertical fields, the wave tilt can be determined.

### D. Field Variation With Distance Methods

The theoretical dependence of field strength upon distance from the transmitter is expressed in terms of the conductivity  $\sigma$  and dielectric constant  $\epsilon$  of the ground. Hence, for a reasonably homogeneous ground, knowledge of the field strength behavior with distance enables one to estimate the local  $\sigma$  and  $\epsilon$ . Theoretical results now exist not only for a uniform flat earth, but for certain inhomogeneous composition spatially varying terrains. A notable example of the application of this technique is the effective conductivity map of the USA estimated by observing the field decay with distance of US commercial radio stations.

## IV DRILL HOLE MEASUREMENTS

### A. Two Loop Methods

The mutual impedance of two loops in an infinite uniform medium is dependent upon the relative orientations, the separation distance, and the medium electrical parameters. It has been shown that under most conditions, the mutual impedance of coaxial loops in a drill hole does not depend upon the presence of the drill hole. Measurements of  $Z_{\text{mutual}}$  of two coaxial loops in a drill hole, to determine  $\epsilon$  and  $\sigma$  have been successfully correlated with alternative ground parameter measurement schemes.

### B. Surface-to-Hole Methods

For a transmitter in a drill hole and a receiver on the surface or vice versa, the field attenuation and phase shift between transmitter and receiver are related to the  $\sigma$  and  $\epsilon$  of the ground.

Knowledge of the geometry of the situation, the patterns and impedances of the transmitter and receiver, and the input power level enables one to use propagation models to estimate  $\sigma$  and  $\epsilon$  for the medium through which the signal passed. Subsurface anomalies, particularly near the surface, can have a decided effect upon the data quality. Signals from distant transmitter can be monitored versus hole depth to ascertain the medium skin depth. Time of arrival measurements can be used for low loss media to determine  $\epsilon$ .

### C. Hole-to-Hole Transmission Methods

For a transmitter in one drill hole and a receiver in a second drill hole, or a second receiver in a third drill hole, there are a variety of methods

of determining  $\sigma$  and  $\epsilon$  of the intervening medium.

For the two drill hole situation, measurement of the absolute attenuation and phase shift (for cw signals) or the time of arrival (for pulse signals) enables one to evaluate  $\sigma$  and  $\epsilon$  of the subsurface. Alternate modes of propagation (e.g., up-over-down and surface reflected) rather than the direct mode can contaminate the data, however, these interference phenomena can also be used to determine the medium properties. For pulse excitation, time of arrival measurements can be used to evaluate  $\epsilon$  and to differentiate relative mode levels. The hole-to-hole method is not useful in media with hole separations of many skin depths. For the three hole situation, the differential phase shift and differential attenuation between two receivers enable one to estimate  $\sigma$  and  $\epsilon$ . The measurement accuracies are not as severe for the three hole situation as for the two hole situation, however, the extra expense of the third hole may not be justified.

#### V. MODEL MEASUREMENTS

In various cases, experimental data for validating theoretical calculations (and the associated measurement scheme) or experimental data for testing the feasibility of a measurement scheme is difficult to obtain for a number of controlled situations. For example, varying the in situ water content, the salt content, the tide level, the geologic constituents, and the geometric locations of transmitter and receiver may be exceedingly difficult, time consuming, and expensive to perform with full scale in situ measurements. In addition, it may be difficult, time consuming, and expensive to obtain numerical results for a theoretical model of the physical situation. When these situations occur, it is sometimes useful to perform scale model experiments. This can be a difficult task for a homogeneous medium, and even more difficult for an inhomogeneous medium. Nevertheless, models for complicated media have been constructed and led to useful results. This method has had extensive use in determining the effect of subsurface anomalies on surface measurement schemes.

#### VI. SAMPLE RESULTS FOR $\sigma$ AND $\epsilon$

There are numerous results for  $\sigma$  and  $\epsilon$  of earth materials under a variety of conditions. Factors which have a decided influence upon  $\sigma$  and  $\epsilon$  are the frequency, the water content, the geological constituents, temperature, weathering factors, and local anomalies, among other factors. "Nominal" results for commonly encountered media can be looked up in tables, however, these numbers should be used with discretion. Due to the variability of  $\sigma$  and  $\epsilon$  from site to site and with environmental factors, it is prudent to determine  $\epsilon$  and  $\sigma$  for a particular site rather than rely on "textbook" values.

It is impossible to briefly summarize the wealth of results for  $\sigma$  and  $\epsilon$  of earth medium. The reader is referred to the references (1-18) for details. Let it suffice to say that  $\sigma$  ( $\epsilon$ ) typically increases (decreases) with frequency. Both  $\sigma$  and  $\epsilon$  nominally increase with water content. A relative ranking of terrain types, with the ones with a larger  $\sigma$  and  $\epsilon$  values listed first, is: sea water, moist ground, medium moist ground, rocky ground, sand, dry sand. Typically, the higher the temperature, the larger  $\sigma$  and  $\epsilon$ .

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## VII. APPLICATION OF MEASUREMENT TECHNIQUES TO PROFILE DETERMINATION

The problem of determining the subsurface profile of a medium (by measurements performed on the surface and/or in drill holes) can be designated as the inverse scattering or inverse transmission problem. The mathematics used to solve electromagnetic ground parameter profile problems also arise and have been used in a number of other physical situations. For example, ground based and satellite-borne remote probing systems are used in atmospheric physics probing techniques based on inverse scattering and inverse transmission data reduction methods.

Measurement methods which have been applied to determining subsurface electrical parameter profiles include four probe (for mineral exploration, location of salt domes, identification of gravel deposits or mineral nodules on the ocean floor), two loop mutual impedance (for detection of buried objects, determining the depth of permafrost), wave tilt (for defining gravel deposits), and multiple mode interference phenomena (for determining depth of the water table, the electrical parameters near the surface of the moon, locating subsurface anomalies surrounding a drill hole, for determining glacial thickness), among others.

Much consideration has gone into data reduction procedures to be used to invert the "inverse data". Procedures which have been successful include least square matrix methods, parameter optimization techniques, iterative approaches, and perturbation methods.

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COMPUTER MODELS FOR ANTENNAS

by

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Presented at

Workshop on Radio Systems  
in Forested and/or Vegetated Environments  
US Army Communications Command  
Fort Huachuca, Arizona

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## COMPUTER MODELS FOR ANTENNAS

A presentation of the Electromagnetics and Systems Research Group, Lawrence Livermore Laboratory. By E. K. Miller.

A summary of wire antenna computer modeling is given with emphasis on the interface problem. The formulation and numerical solution methods are summarized and applications demonstrated with numerous examples. The complete article is available as a Lawrence Livermore Laboratory report, UCRL-75206, 12 Nov. 1973.

### Acknowledgment:

Besides the specific contributions made to this article by the individuals explicitly mentioned in the references and figures, various members of the Electromagnetics and Systems Research Group have been instrumental in developing the computer codes and methods referred to or for which data were presented. They are R. W. Adams, Jr., R. M. Bevensee, F. J. Deadrick, J. A. Landt, D. L. Lager, R. J. Lytle, and A. J. Poggio.

## COMPUTER MODELS FOR ANTENNAS

### I. INTRODUCTION

Numerical methods based upon integral equation formulations are receiving increasing acceptance for application to real-life electromagnetic radiation and scattering problems. Computer codes have been developed and validated for both surface and wire geometries in both the frequency and time domains for modeling infinite, homogeneous medium problems. Some of these basic procedures have also been extended to the analysis of structures located near a planar interface. In this presentation we will discuss the general topic of computer models for wire antennas from a frequency domain viewpoint with emphasis directed to antennas located near the ground-air interface. Some preliminary considerations are discussed in Section II below, followed by a brief summary of a specific formulation and numerical treatment in Section III, with sample numerical results given in Section IV.

### II. PRELIMINARY CONSIDERATIONS

The derivation of an integral equation for a wire structure can be accomplished in many ways. What is basically involved is the writing of Maxwell's Equations in integral form so that the scattered or secondary fields are given in terms of integrals over induced source distributions. By expressing the secondary field over loci of points where the total field (incident or primary plus secondary) behavior is known via boundary or continuity conditions, an integral equation for the induced source is obtained in terms of the primary field. Two broad general classes of integral equations are obtained, depending upon whether the forcing function (primary field) is electric or magnetic. The former gives rise to a Fredholm integral equation of the first kind, so called because the unknown appears only under the integral. A Fredholm integral equation of the second kind, in which the unknown also appears outside the integral, is obtained from the latter. While derivatives of the unknown may occur as well, these equations are commonly called integral equations rather than integro-differential equations as would be strictly correct.

Generally speaking, it has been found that the magnetic-field type integral equation is better suited for smooth, closed surfaces than it is for thinplate or shell geometries and wires (Poggio and Miller, 1973). The converse is generally true of the electric-field type integral equation. It is the latter then that is most commonly employed for treating wire structures. Also involved in developing wire integral equations are the approximations that: (1) the circumferential current is negligible; (2) the circumferential variation of the longitudinal current can be ignored; and (3) the thin-wire or reduced kernel can be used in place of the actual surface integration.

Many analytically equivalent integral equations for wires based upon the electric-field can be derived. Three of the most commonly employed are the Hallen or vector potential type, (Mei, 1965), the scalar-vector potential version (Harrington, 1968), and the Pocklington integral equation (Richmond, 1965). All are solved within the framework of the moment (or matrix) method but each exhibits distinctive characteristics which must be taken into account in its numerical treatment. The Hallen equation for example can produce results using a pulse current basis of accuracy comparable to those obtained from the Pocklington equation solved with a three term (constant, sine and cosine) basis for simple structures (Miller and Deadrick, 1973). The Hallen equation is not however, readily extendable to the complex geometries that the Pocklington equation can handle (Butler, 1972).

It can be appreciated that there are many options available to the analyst concerning the integral equation to be selected and its numerical treatment in developing a computer model for application to wire antennas. A brief overview of the relevant equations and numerical treatment used for free space and various interface theories and some special topics is given in the next section.

### III. WIRE ANTENNA ANALYSIS

#### A. Infinite Homogeneous Media

The Pocklington-type integral equation for a wire structure of contour  $C(\bar{r})$  can be expressed in the form

$$\hat{s} \cdot E(s) = \frac{i\omega\mu}{4\pi} \int_{C(\bar{r})} I(s') G_0(s, s') ds'; \quad s \in C(\bar{r}), \quad (1)$$

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Reduction of this equation to matrix form involves: (1) approximating  $C(\bar{r})$  as a piecewise linear sequence of  $N$  segments of length  $\Delta_i$ ,  $i=1, \dots, N$ , so that  $C(\bar{r}) \approx \sum_{i=1}^N \Delta_i \hat{s}_i$  with  $\hat{s}_i$  the unit tangent vector to  $C(\bar{r})$  at  $\bar{r} = \bar{r}_i$  (use of straight segments is not mandatory, but very convenient in simplifying the current integration); (2) introduction of the subsectional bases  $I_i(s') = A_i + B_i \sin(s' - s_i) + C_i \cos(s' - s_i)$  to represent the unknown current [the final unknowns will be the  $N$  sampled current values  $I_i = A_i + C_i$ ,  $i=1, \dots, N$  at the center of each of the  $N$  segments]; (3) a current interpolation procedure whereby the individual  $A_i$ ,  $B_i$ , and  $C_i$  constants are expressed in terms of the sampled current values; (4) use of the  $N$  delta function weights  $\delta(s - s_i)$ ,  $i=1, \dots, N$  to obtain an  $N$ th order impedance matrix of  $N$  independent field equations; [note the weight functions sample the field at the segment centers, and are thus "collocated" with the current sample locations]; (5) specification of the  $N$  incident or primary field vector components  $E_i = E^I(s_i) \cdot \hat{s}_i$ ,  $i=1, \dots, N$  which are the tangential fields at the  $N$  segment centers; (6) matrix manipulation to obtain an admittance equivalent of the impedance matrix; and (7) computation of the current distribution and whatever field components, if any, are desired. The total computer solution time is well approximated by  $AN^2 + BN^3$  where the "A" term corresponds to step 4 and the "B" term to step 6. For the code under consideration here and for a CDC-7600 computer,  $A \approx 4 \times 10^{-4}$  and  $B \approx 2 \times 10^{-6}$  seconds.

#### B. Perfectly Conducting Half Space

Equation (1) as written applies to wire structures excited as antennas or scatterers and located in infinite, isotropic, homogeneous media of arbitrary (possibly lossy) permittivity and permeability. Its extension to permit the modeling of magnetic or electric image planes is easily accomplished. For example, the perfectly conducting ground analog of Equation (1) is, for an antenna elevated above a ground plane at  $z=0$ ,

$$s \cdot \vec{E}(s) = \frac{i\omega\mu}{4\pi} \int_{C(\bar{r})} I(s') \left[ G_0(s, s') + G_1(s, s') \right] ds' \quad (2)$$

### C. The Imperfectly Conducting Half Space

A problem which is not so computationally simple to handle, however, and one which is of perhaps greater practical interest is that of an antenna located (buried or elevated) near the ground-air interface. This is a topic of considerable longevity in electromagnetics; a formal solution was worked out for this problem in 1909 by Sommerfeld. The numerical complexity of evaluating the Sommerfeld integrals (which appear in the integral equation kernel) for arbitrary source and observation point locations and ground parameters however, have prevented the Sommerfeld theory from being routinely used for such problems. Consequently, while progress in applying the Sommerfeld theory has been achieved, alternative approaches to the antenna-ground problem have also been pursued. A brief discussion of these various methods is given below.

#### 1. The Sommerfeld Theory

Details of the steps in deriving the Sommerfeld integrals may be found elsewhere (Sommerfeld, 1964). Here we will simply write one version of Equation (1) which accounts for the interface reflected field via the Sommerfeld theory; alternative forms are also available and differ essentially in how the perfect-ground image terms are handled. It is

$$\begin{aligned} \hat{s} \cdot \bar{E}(s) = \frac{i\omega\mu}{4\pi} \int_{C(\bar{r})} I(s') ds' & \left\{ G_0(s, s') + G_1(s, s') \right. \\ & + \left( \cos \beta + \frac{1}{k^2} \frac{\partial^2}{\partial s \partial z} \right) \sin \beta' g_{Hz} - \cos \beta' g_{Vz} \\ & \left. + \sin \beta' \left( \sin \beta \cos(a-a') + \frac{1}{k^2} \frac{\partial^2}{\partial s \partial t'} \right) g_{Ht} \right\} \quad (3) \end{aligned}$$

The Sommerfeld integrals are denoted by  $G_{Hz}$ , etc.

The presence of the double integral in Equation (3), particularly the Sommerfeld portion, makes it quite time consuming and sensitive to evaluate. In spite of that, the basic moment method can be used to solve it, but in addition to the usual constraints imposed on current sampling, it is necessary to take into account the source distance from the interface.

## 2. Modified Image Theory

In many cases, although they may not a priori be always easy to identify, the rigor represented by Equation (3) is unnecessary; various approximations will be found adequate. The accuracy actually required of the computer model may be debatable, but it is probably reasonable to seek something on the order of experimental error. One approach which has been found, for simple antennas, to agree within 10-15% of the Sommerfeld results for input impedance, and so which appears useful in view of the above observation, is the reflection coefficient approximation (Miller et. al., 1972a, 1972b). It involves representing the interface-reflected field in terms of their perfect-ground images multiplied by the Fresnel plane wave reflection coefficients for the TE and TM field components evaluated at the specular reflection point. This approximation leads to the integral equation given below.

$$\begin{aligned} \hat{s} \cdot \vec{E}(s) = & \frac{i\omega\mu}{4\pi} \int_{C(\vec{r})} I(s') \left[ G_0(s, s') \right. \\ & + R_M G_z(s, s') \\ & \left. + \left( R_E - R_M \right) \sin\theta \sin\theta' \sin(\phi - \alpha) \sin(\phi - \alpha') g_1(\vec{r}, \vec{r}') \right] ds' \end{aligned} \quad (4)$$

where  $R_E$  and  $R_M$  respectively are the usual TE and TM reflection coefficients.

(Although written expressly for the reflected field, an expression similar to (3) and (4) also holds for the field transmitted across the interface.) Since the reflection coefficient integral equation differs only trivially from that for the perfect ground case given by (2), it may be appreciated that its numerical solution is obtained with almost equal efficiency, in marked contrast to the situation which holds for the rigorous theory. The reflection coefficient approximation is, in addition, applicable to a laterally inhomogeneous ground with little further complication. Layered grounds can also be handled using this approach.

### 3. The Compensation Theorem

Application of the compensation theorem to ground-plane problems has received considerable attention (Monteath, 1951; Mittra, 1961; King, 1969b). It has been used to determine the input impedance of vertical monopoles located over various ground configurations, including determining the effect of ground screen size. However, more general antenna problems have evidently not been attempted with this theory. The reason for this lies apparently, not in limitations inherent in the theory itself, but in its numerical implementation. A ground plane integral is involved, which, for all but the simplest situations, requires numerical evaluation.

The compensation theorem "is essentially an exact perturbation technique in which the fields in the unperturbed state are known" (King, 1969b). If the unperturbed state is the case of a perfectly conducting ground plane and the perturbed state is the actual ground problem of interest, then we obtain for the antenna input impedance.

$$Z' = Z + \frac{1}{I^2} \int_A \bar{H} \cdot \hat{z} \times \bar{E}' da$$

with perturbed quantities denoted by primes and  $I$  the feed point current. Since the perfect ground magnetic field distribution can be accurately solved for, evaluation of  $Z'$  hinges on finding  $\bar{E}'$ . This is usually accomplished by using the surface impedance approximation, i.e.  $E'_{\tan} = -H'_{\tan} Z_{\text{surf}}$  and then assuming  $H'_{\tan} \approx H_{\tan}$ . These steps facilitate the calculation and permit use of the perfect ground result as a sort of canonical solution to find the antenna impedance for the finitely conducting ground.

### 4. Geometrical Theory of Diffraction

The Geometrical Theory of Diffraction (GTD) does not have obvious application to antenna-ground problems. There are, however, two areas where GTD may be beneficial: (1) ground-screen edge effects (diffraction) on input impedance and low angle radiation; and (2) effects of large scale terrain variations, e.g., diffraction at a cliff. Application of GTD to

both areas has been studied by Thiele (1973). His approach was to combine GTD with the moment method to find the effect of the edge diffracted field on the current distribution of a monopole antenna located on a wedge. This leads to an integral equation modified from that for free space by inclusion of the diffracted fields, given in terms of the antenna current in the total tangential electric field on the antenna. Thus, no additional unknowns are involved. The far-field is treated in a similar manner. Results obtained to date are encouraging, although use of the technique to analyze a real ground screen awaits derivation of diffraction coefficients for a perfectly conducting half-plane lying on a lossy interface.

#### D. Special Topics

In addition to the above topics, there are other problem areas concerning wire antenna computer modeling that deserve attention. Some of them are summarized here.

##### 1. Impedance Loading

In many cases of interest, the antenna may be connected to impedance loads of various kinds, or may even itself be lossy enough that it cannot be accurately modeled as being perfectly conducting. These situations can be accommodated in the computer model by subtracting an appropriate voltage

drop  $Z_{ij}^{(L)} I_j$  from the source term  $E_i$ , where  $Z_{ij}^{(L)}$  is the

load impedance. When there are no mutual impedance effects, such as due to transformer or transmission line

interconnection, for example, then  $Z_{ij}^{(L)} = \delta_{ij} Z_{ij}^{(L)}$ , i.e.,

the  $\bar{Z}$  matrix becomes diagonal. Lumped loads are simply specified in terms of their resistive and reactive components. Their treatment is similar to that accorded sources, since the two can be viewed as mathematically equivalent. Distributed loads which might be used to model wire losses, can be derived from the wire properties (Cassidy and Fainberg, 1960).

## 2. Sheathed Wires

Another problem of relevance, especially for antennas located in lossy media such as ground or sea water, is that of a wire coated by a dielectric layer. It has been suggested, but not demonstrated, that the sheath could be modeled in the same way as a lossy wire, by a suitably derived impedance load (Miller, et. al., 1970). An alternative, more rigorous approach has been taken by Richmond (1973) who models the sheath with a radially directed polarization current, reasoning that the tangential field, being much smaller, is by comparison of negligible import. Since the radial sheath fields which determine this current are known in terms of the charge density on the wire, no additional unknowns are introduced. One simply obtains a modified integral equation which can be solved in the usual way.

## 3. Time Domain Analysis

Previous discussion has dealt exclusively with frequency domain formulations. It is worthwhile to point out that these problems can also be attacked from a time-dependent or time domain viewpoint (Bennett and Weeks, 1968; Miller, et. al, 1973a, 1973b). As one outcome of such an effort, there can be derived time-dependent integral equations which correspond closely to their frequency domain counterparts. The solution procedure, while also developed from the moment method is significantly different in that a solution is obtained as an initial value problem via time stepping. This leads to results which are valid for only a single incident field or source configuration but over a band of frequencies, in contrast to the more familiar frequency domain approach of which the converse is true. Solution may consequently be obtained more efficiently in the time domain than the frequency domain for certain problem types, especially for wire structures analyzed as antennas.

## 4. Ground Screens

The compensation theorem has been employed in various ways to analyze ground screen effects as mentioned above. The reflection coefficient approximation has also been used for

this purpose. It offers an easily implemented procedure for analyzing a broad class of ground screen configurations with greater efficiency than available in general from the compensation theorem.

What is essentially required in order to include the ground screen influence in the reflection coefficient calculation is a modified reflection coefficient which takes into account the reflecting properties of the screen-ground combination. This is possible if the surface impedance of the combination is known. For ground screens whose wires are in good electrical contact with the soil, the effective surface impedance  $Z'_{\text{surf}}$  may be taken to be (Wait, 1969)

$$Z'_{\text{surf}} \approx \frac{Z_{\text{surf}} Z_{\text{screen}}}{Z_{\text{surf}} + Z_{\text{screen}}}$$

where  $Z_{\text{screen}}$  is the screen impedance. For a radial screen having  $N$  wires of radius  $a$ , the screen impedance at distance  $\rho$  from the center is given by (Wait, 1969)

$$Z_{\text{screen}} \approx \frac{i\omega\mu\rho}{\lambda} \ln(\rho/\lambda a)$$

A corresponding formula for a parallel grid of wires whose center spacing is  $d$  is

$$Z_{\text{screen}} \approx \frac{i\omega\mu d}{2\pi} \ln(d/2\pi a)$$

Meshes consisting of locally orthogonal wires having different spacings might be treated as anisotropically conducting planes whose principal direction impedances are obtained from the parallelwire formula using their corresponding spacings. From  $Z'_{\text{surf}}$  we infer an effective ground permittivity for use in computing the Fresnel reflection coefficients, and are thus able to include the screen in the integral-equation calculation. The anisotropic case requires decomposition of the TE and TM fields into components along the orthogonal screen wires. Note that this method fails for vertical antennas located at the center of a radial screen.

An alternative possibility is offered by the work of Astrakahan (1964) who derived reflection coefficients for infinite plane wire grids. His results, given in terms of TE-TE, TM-TM, TE-TM, and TM-TE reflection coefficients can be modified to include the effect of the ground itself and used in the reflection coefficient approximation. Of the above, only the radial-wire screen analysis has been implemented.

#### 5. The Layered Ground

Reflection coefficients are of course available for a layered ground. For the special case of only two layers, and where the surface impedance approximation holds, the effective surface impedance is given by (Wait, 1962)

$$Z'_{\text{surf}} \approx Z_{\text{surf}} \frac{\sqrt{\epsilon_1} + i\sqrt{\epsilon_2} \tan kh \sqrt{\epsilon_1}}{\sqrt{\epsilon_2} + i\sqrt{\epsilon_1} \tan kh \sqrt{\epsilon_1}}$$

with  $\epsilon_1$  and  $\epsilon_2$  the relative permittivities of the two layers and  $h$  the thickness of layer 1.

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A COMMUNICATION CHANNEL SIMULATOR  
FOR FORESTED AND VEGETATED ENVIRONMENTS

by

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Presented at

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in Forested and/or Vegetated Environments  
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## I. INTRODUCTION

Newly designed tactical communications equipment is usually field tested to determine its performance during operational conditions. Such field environments may involve tropic, arctic, desert, mountain, and other worldwide areas. Implementation of such tests incur considerable expenditure of time, manpower, equipment and personnel inconvenience, especially when operating in adverse areas.

The U. S. Army Electronics Command (USAECOM) has recently developed a Tactical Channel Simulator (TCS) that recreates in the laboratory the signal effects that tactical VHF channel transmissions experience during actual field operations. Such effects as signal dispersion, fading, and noise are characterized by the simulator.

At USAECOM, the TCS has become a tool for laboratory evaluation of VHF communications equipment. It is being used to compare the performance of various modem designs for operation in specific propagation environments. Not only does this facility enable designs to be optimized on an iterative basis, but the work can be done without the delay and high costs associated with extensive field testing--and the results are available immediately.

## II. SYSTEM DESCRIPTION

The TCS system operates in the VHF range of 40 MHz with a bandwidth capability of 100 KHz. The system consists of a prober, an analyzer, and a simulator. The prober generates and transmits pseudo-random impulses; the analyzer receives, analyzes, processes, and records on tape the impulse channel response (time-varying parameters) of the transmission channel.

The tape is then used with the channel simulator in the laboratory to reproduce the recorded channel characteristics. Signals from the communications system under test are also fed into the simulator and the resultant channel effects determined. Both digital and analog type signals can be accommodated.

The prober and analyzer are used during field operations to make the tapes. Once accomplished, only the simulator and the tapes are needed for channel reproduction. The basic element of the TCS is a tapped delay line and associated circuitry. The delay line contains 9 incremental elements of 3.3 microseconds each. Selection of various delay tap combinations are made to correspond to various multipath conditions.

The gain from each tap is controlled by the channel impulse response recording which contains the channel disturbance characteristics. The resulting signal from the simulator therefore incorporates the same channel disturbances.

Perturbations may also be introduced into the channel, such as:

- A. Doppler shift as caused by an airplane flying in the propagation path.
- B. Phase Jitter.
- C. Additive noise.

The simulator can provide either a fixed multipath structure or the variable structure from the recorded tapes. The fixed multipath is introduced by manually setting front panel switches. Figure 1 is a picture of the channel simulator. Figure 2 a simplified block diagram of the simulator, showing its major functions.

### III. LIBRARY OF TAPES

At present, USAECOM has a library of 16 stored channel tapes that represent 3 general environments:

A. Steep rolling hills, mostly wooded with some clearing of the slopes for pasture. Practically no moving vehicles or aircraft were in the vicinity during the tests.

B. Mild rolling hills, with rather dense, second growth woodland. The sites were adjacent to roads that carried considerable auto and truck traffic, with commercial aircraft present occasionally.

C. Light to medium residential areas, with farmland and woods; considerable vehicular and aircraft traffic was present.

Path distances varied from 5 to 25 miles. Each tape corresponds to 30 minutes of operation.

It should be remembered that the simulation capability is primarily limited by the library of tapes that characterize the various real-life media and conditions.

### IV. TESTS

Laboratory and field tests have confirmed the capability of the channel simulator to repeatedly reproduce selected transmission channel effects, both statically and with recorded tapes.

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Figures 3 and 4 demonstrate the performance of the simulator. Figure 3a shows the frequency spectrum of the channel simulator output signal when the simulator is fed with pseudo-random impulses from the prober with no delays; this is equivalent to a "no-multipath" condition. Figure 3b shows the resulting multipath when delay is introduced. Figure 4a shows the simulator output when fed with signals from the Army's AN/VRC-12, a tactical communication transceiver, and incorporating no delay. Figure 4b shows the multipath effects with delay. During normal simulator operation, however, the individual tap gain and phase variations are controlled by the channel tape recordings.

#### V. PLANS

Plans are currently underway to extend the TCS capability to include UHF frequencies. The tape library will also be increased by repeating at UHF frequencies the field tests that were performed earlier at VHF. Additional tests will be made with one of the terminals in a moving vehicle on the ground.

#### VI. PARTICIPATION OF OTHERS

It is unfortunate that the TCS was unavailable when the SEACORE field work was being done--the most complete collection of tapes that characterized the SEA propagation environment could have resulted.

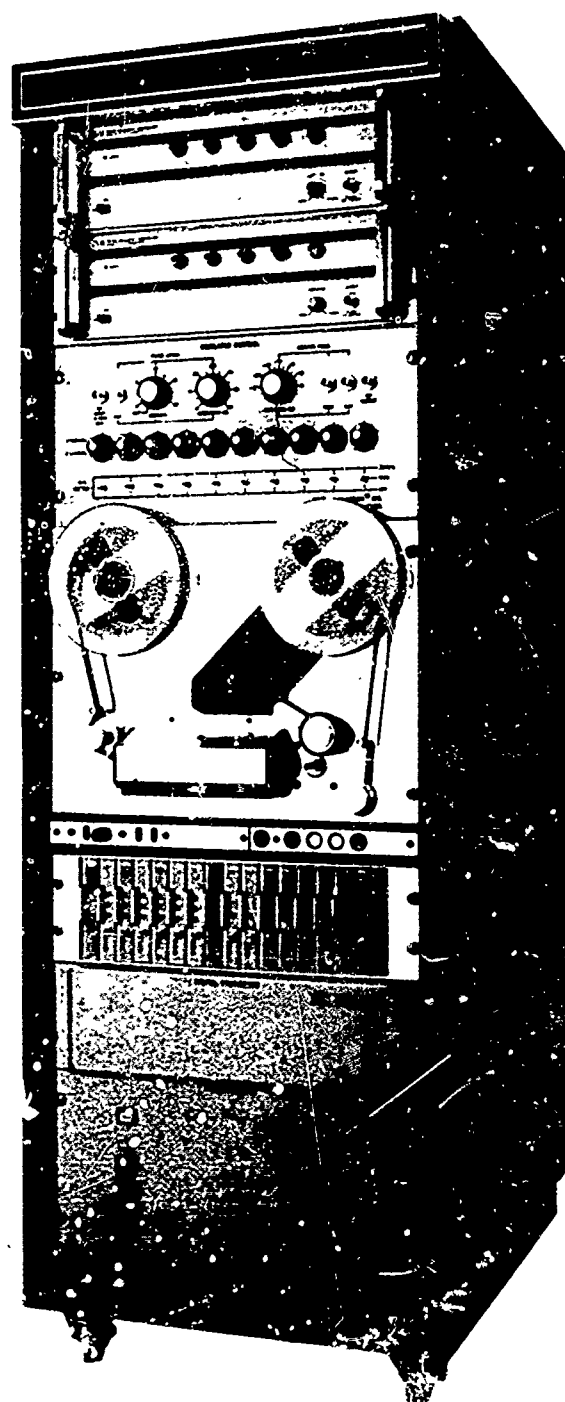
For the Channel Simulator to be used extensively by engineers in the design and evaluation of communication systems and techniques, a greatly expanded tape library is required. This family of tapes should include jungle and tropical areas, desert, arctic, urban, rural, and involve ground-to-ground, air-to-ground and other propagation modes.

An invitation is extended to organizations desiring to use the Tactical Channel Simulator facility, and to also participate in efforts to expand the tape library. This is extremely important, since ECOM cannot do it alone.

The TCS system was accomplished through the efforts of Mr. Bernard Goldberger and his staff at USAECOM working in conjunction with the Signatron Corporation.

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Tactical Channel Simulator

Fig. 1  
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# TACTICAL CHANNEL SIMULATOR

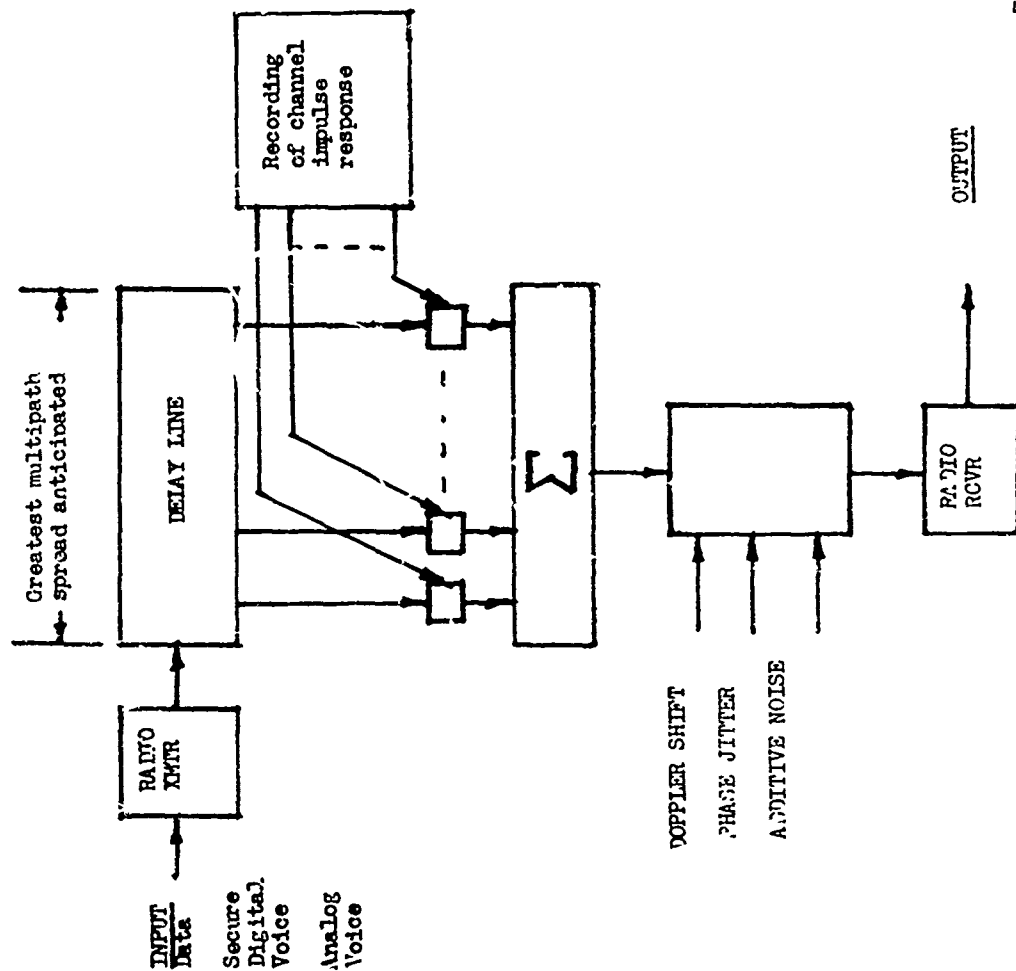


Fig. 2

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FREQUENCY SPECTRUM  
OUTPUT OF TACTICAL CHANNEL SIMULATOR  
(PROBER FEEDING SIMULATOR DIRECTLY)

(a)



USING TAP 1 ONLY - (SINGLE PATH EQUIVALENT)  
(SCAN WIDTH = 5 KHz./DIV)  
(VERTICAL CALIB = 10DB/DIV)

(b)



USING TAPS 1 & 2 - (MULTIPATH EQUIVALENT)

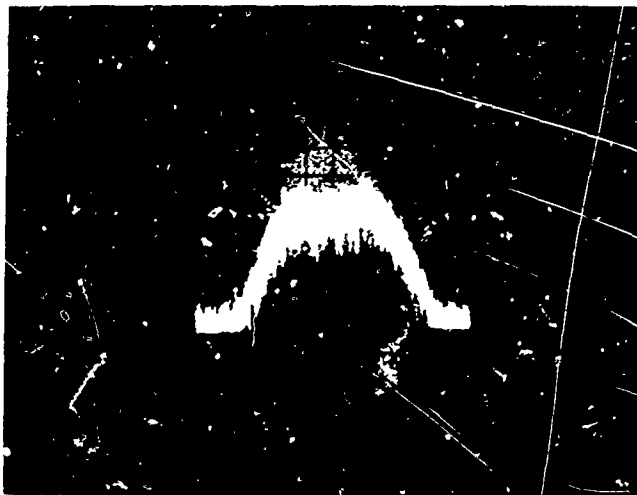
FIG. 3

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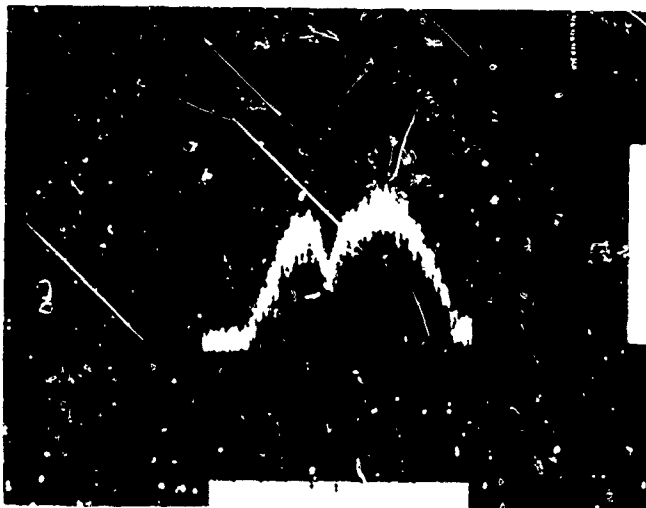
FREQUENCY SPECTRUM  
OUTPUT OF TACTICAL CHANNEL SIMULATOR  
AN/VRC-12 FEEDING SIMULATOR

(a)



USING TAP 1 ONLY - (SINGLE PATH EQUIVALENT)  
(SCAN WIDTH = 5KHz/DIV)  
(VERTICAL CALIB = 10 dB/DIV)

(b)



USING TAPS 1 & 10 - (MULTIPATH EQUIVALENT)

FIG. 4  
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CONSIDERING FOREST VEGETATION AS AN  
IMPERFECT DIELECTRIC SLAB

by

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Presented at

Workshop on Radio Systems  
in Forested and/or Vegetated Environments  
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## Considering Forest Vegetation as an

### Imperfect Dielectric Slab

Alfred H. LaGrone

A study was conducted by Pounds and LaGrone (1963) to determine the feasibility of modeling a forest by a lossy dielectric slab. The object of the study was to provide a mathematical model whereby the effects of the forest on the propagation of electromagnetic waves into and through the forest could be determined. The model of the forest was obtained by describing the forest as a dielectric mixture. The theory of artificial dielectrics (Kock, 1946; Kock 1948) was used in obtaining the real and imaginary part of the dielectric permittivity.

Considerable attention was given to the development of a statistical description of a fully stocked, moderately dense, even-aged forest stand. These statistics included such things as the number of trees per acre, average diameter at breast height, basal area per acre, average heights, estimated or measured volumes of wood and bark per acre as a function of age and characteristics of the site. A description of the foliage, including such things as shape, size and some variations from species to species was developed. The electrical properties of wood, bark, and leaves were reported.

In developing the mathematical model of the forest, tree leaves were considered as conducting bodies; bark and wood were treated as dielectric bodies. From dielectric mixture theory, the dielectric constant of the forest was calculated. This gave the real part of the complex permittivity. The imaginary part of the complex permittivity was determined from loss measurement reported by LaGrone (1960). The final electrical model was then described by the complex permittivity  $\epsilon_c$ , where

$$\epsilon_c = \epsilon' - j\epsilon'' = (1.2370 - j 9.06 \times 10^{-9}) \epsilon_0$$

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A NOVEL GRAPHICAL TECHNIQUE FOR  
SPECTRUM UTILIZATION/COMMUNICATIONS PLANNING

by

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Presented at

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"A NOVEL GRAPHICAL TECHNIQUE FOR  
SPECTRUM UTILIZATION/COMMUNICATIONS PLANNING"

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ABSTRACT

This paper describes a new technique whereby the communications power budget is divided into equipment-dependent and equipment-independent terms thereby permitting non-technical personnel to rapidly determine the adequacy of a given piece of communications gear for a specified mission. Optimization of frequency selection is achieved by means of a simple transparent overlay characterizing effective radiated power vs. frequency for the equipment in question.

I. INTRODUCTION

In a recent study (1) of Naval Inshore Warfare (NIW) communications requirements, it was found that a need exists for simpler techniques of translating analysis of radio systems performance into useful tools for mission communications planning. In particular, planners must be able to rapidly assess the adequacy of given pieces of communications gear for specific missions in order to minimize the size/weight burden placed on field personnel.

A novel graphical technique was discovered in the course of this study which has already proven quite useful to the NIW community. Since it is felt that this technique is generally applicable to communications planning, it may prove of value in the practical implementation of the quantitative understanding of antenna and propagation effects in forested/vegetated environments which emerge from this workshop.

II. OUTLINE OF TECHNIQUE

In order to facilitate rapid assessment of the utility of a given piece of communication equipment in a specified tactical situation, it will prove convenient to divide this evaluation process into two distinct steps:

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Step 1: determine how much power would be required to communicate over the desired distance assuming the receiver/transmitter combination (and associated antennas) to be of some conveniently defined standard configuration.

Step 2: determine for the specified equipment in question whether the actual radiated power exceeds the required power by a sufficiently great margin to allow for: (1) uncertainties in the assumed values for the communications model (e.g., antenna gains, noise power, basic transmission loss, etc.) and, (2) differences between the actual equipment and the standard configuration assumed in Step 1.

The value of this approach is that the Step 1 analysis, being independent of equipment specifics can be performed once and for all for a given tactical environment. Embodying as it does the consideration of external noise and basic transmission loss--usually the most analytically complex of the communication model parameters--it saves unnecessary repetition of such calculations when evaluating several pieces of equipment for the same communications role.

The "standard" configuration assumed in Step 1 is defined as follows: (See figure -1.)

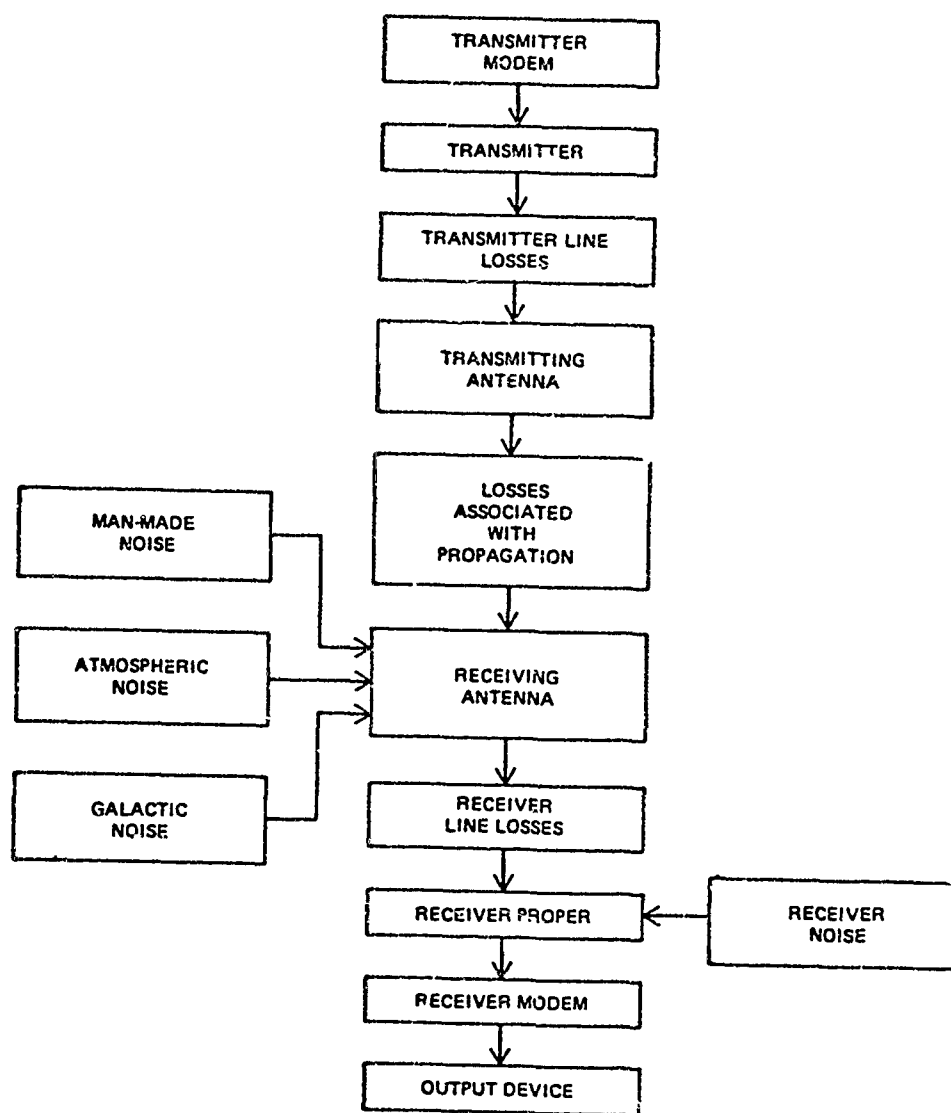
- a. type of modulation: voice, Double Side Band AM (DSB-AM)
- b. noise limiting: none
- c. receiver noise: none
- d. transmitter and receiver antennas: standard (vertically polarized) isotropic antennas located at the earth's surface
- e. grade of service: just usable quality (90 percent sentence intelligibility)
- f. transmission line losses: none

The transmitter power required for communication over a ground range D under the above conditions is determined from the equation:

$$P_T - L_B(D) - N_1 = (C/N_1)_{\text{DSB-AM}}^{90\%} \quad 1)$$

where:

- $P_T$  = Transmitter power in dBW
- $L_B(D)$  = Basic transmission loss (for the type of propagation and terrain under consideration) at distance D in dB



(U) Figure 1. Communication system model.

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$N_1$  = Noise power density (i.e., noise power in a 1 Hz band) at the receiving antenna terminals in dBW/Hz

$(C/N_1)_{90\%}^{DSB-AM}$  = Carrier to noise power density ratio in dB-Hz required to provide 90% sentence intelligibility in a DSB-AM receiver under stable (i.e., non-fading) propagation conditions

Renaming  $P_T$  the "required effective radiated power" (RERP) we have from 1):

$$\text{RERP in dBW} = (C/N_1)_{90\%}^{DSB-AM} + L_B(D) + N_1 \quad 2)$$

Once the desired propagation path and the noise environment have been specified, the required effective radiated power as defined in 2) becomes a function only of the carrier frequency.

The actual communications system under consideration (see figure 1) will in general differ in its characteristics from the "standard" configuration assumed in the definition of the RERP. It will not, therefore, suffice to merely compare the actual transmitter power with the RERP in order to determine whether or not the actual system is acceptable for communications, since the specific deviations from the "standard" configuration must be explicitly taken into account.

To accomplish this, we define the "actual effective radiated power" (AERP) as follows:

$$\text{AERP in dBW} = P_T^a + G_{AT} = G_{AR} - P_{LT} - P_{LR} + G_{SP} = \Delta N_R \quad 3)$$

where:

$P_T^a$  = actual transmitter power in dBW

$G_{AT}$  = actual transmitting antenna gain in direction of propagation path to received in dB above isotropic

$G_{AR}$  = actual receiver antenna gain in direction of propagation path to transmitter in dB above isotropic

$P_{LT}, P_{LR}$  = transmitter, receiver transmission line losses in dB

$G_{SP}$  = signal processing gain (arising from modulation schemes other than DSB-AM and/or error rate requirements other than 90% sentence intelligibility) in dB relative to DSB-AM-90% sentence intelligibility. Equivalently,

$$G_{SP} = -(C/N_1)^{\text{actual}} + (C/N_1)_{90\%}^{DSB-AM}, \text{ where } (C/N_1)^{\text{actual}}$$

is the required carrier to noise power density ratio for the actual grade of service under consideration.

$\Delta N_R$  = receiver noise correction in dB, whose form depends on whether or not the system is receiver noise limited.

if receiver noise limited,  $N_R$  = receiver noise power density in dB relative to the external noise power density

if external noise limited,  $N_R = -G_{AR} + P_{LR}$

When the actual effective radiated power as determined from equation 3) equals or exceeds the required effective radiated power as given by 2), then communication with the desired grade of service is theoretically possible over the propagation path specified. In practice, one would prefer that the AERP exceed the RERP by a margin of safety to accommodate the uncertainties in the values used for the communication model parameters as well as unpredictable propagation effects such as fading and larger-than-normal atmosphere or man-made noise.

### III. EXAMPLES

Figures 2 and 3 show RERP vs. frequency as computed from equation 2) in two environments. In constructing these curves, we have utilized the criterion (2)

$$(C/N_1)_{90\%}^{DSB-AM} = 50 \text{ dB} \cdot \text{Hz}$$

and noise data as given in CCIR Report 322 and the ITT Handbook. Those for a tropical forest from reference 3. For illustrative purposes, we have included representative skywave modes as computed via the techniques of reference 4. It is to be emphasized that figures 2 and 3 are not universally applicable but are merely typical of what one would compute for a given area of the world at a specific time. Thus, a communications planning manual would consist of a number of such curves, catalogues according to day of the year and locale.

Figure 4 shows a typical overlay of AERP vs frequency for two pieces of equipment. Implicit in these curves are the frequency-dependent antenna efficiencies.

An overlay such as that of Figure 4 need only be generated once and can be applied to various environments such as those of figures 2 and 3. It is only necessary to place an AERP overlay on top of an RERP family of curves and to note the threshold range where AERP exceeds RERP by a suitable safety margin (typically 10-15db). It is evident that frequency, antenna and/or modulation optimization follows immediately by inspection, without requiring any numerical computations on the part of the analyst.

### IV. SUMMARY AND RECOMMENDATIONS

A novel communications planning tool has been introduced which greatly simplifies power budget analysis. Consideration of its possible value in the practical utilization of the results of this workshop would appear to be warranted.

# THRESHOLD FOR COMMUNICATION; OVER LAND, SUMMER, NEAR URBAN AREA

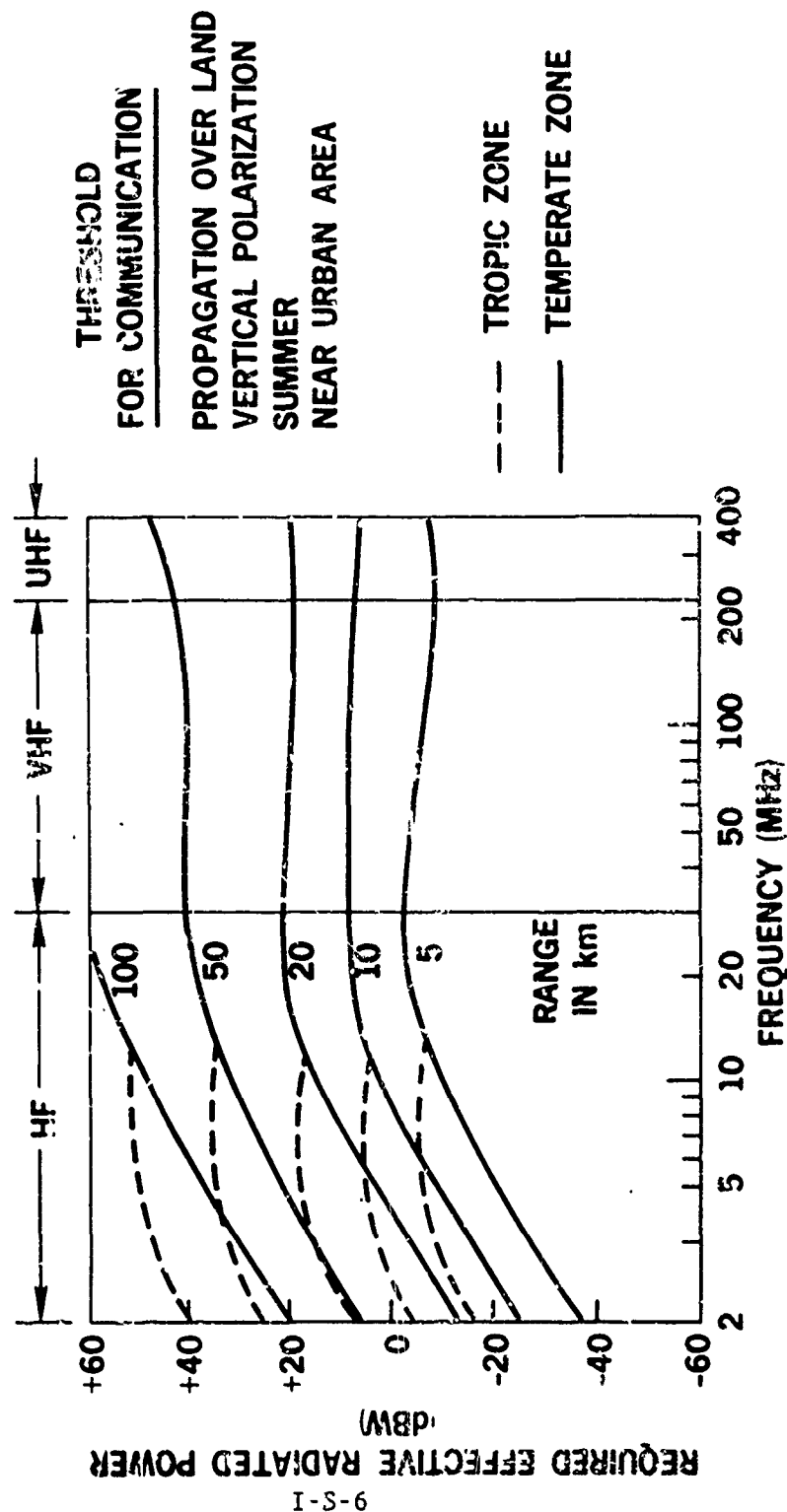


Figure 2. Threshold for communication in urban areas.

# THRESHOLD FOR COMMUNICATION; LOW VERTICAL ANTENNAS

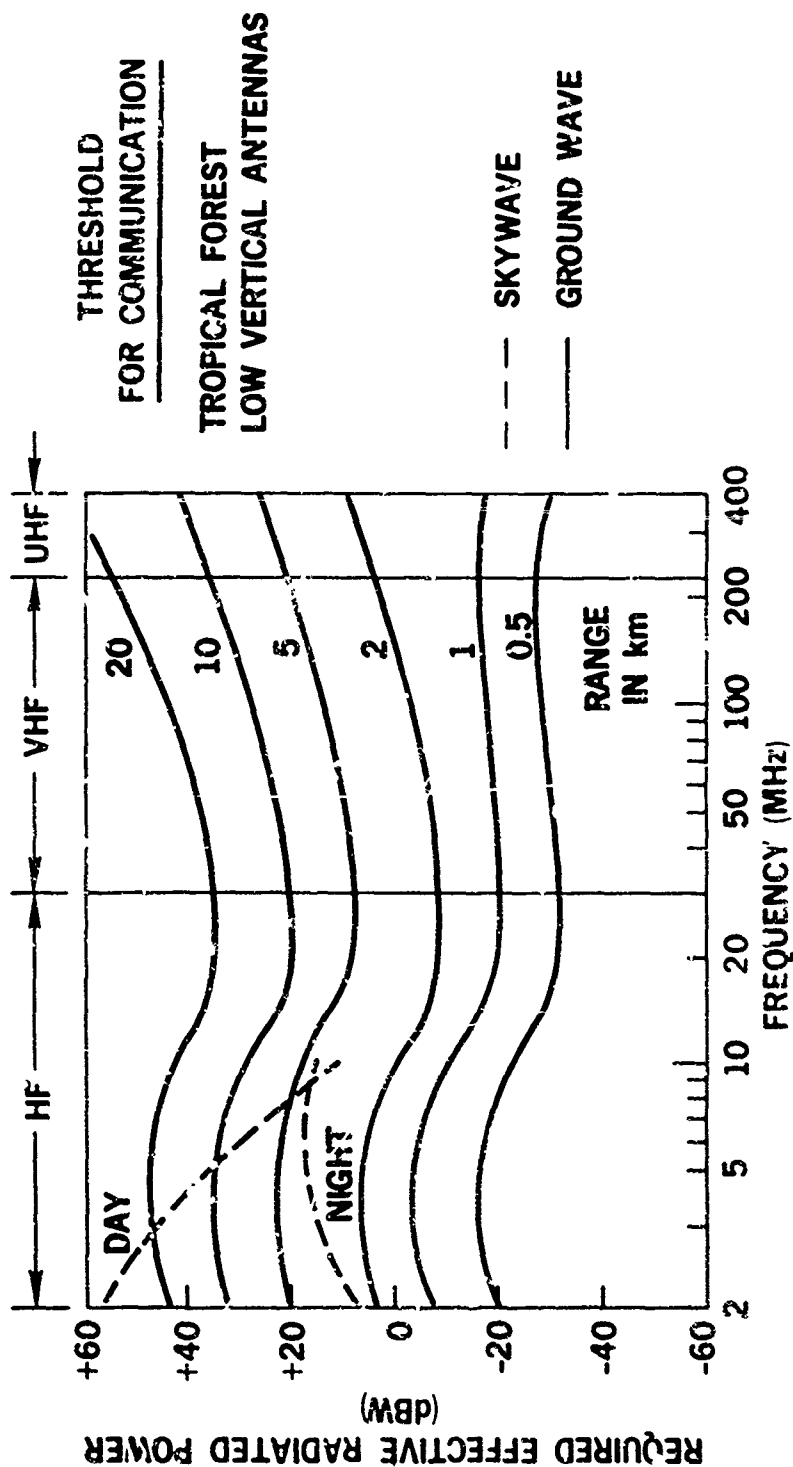


Figure 3. Threshold for communication; tropical forest.

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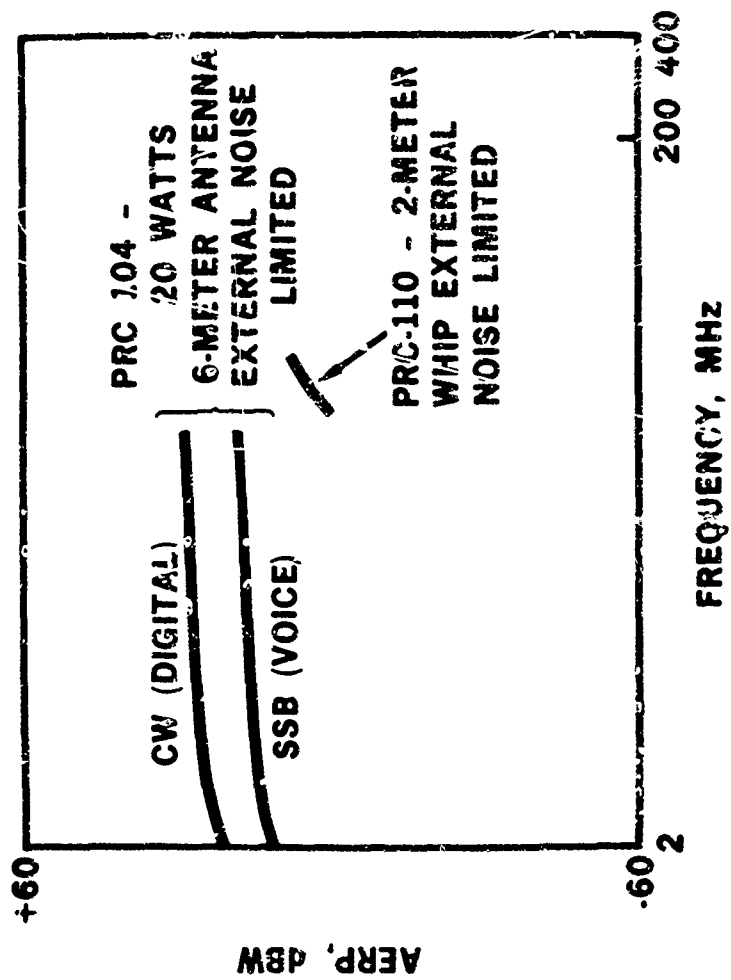


Figure 4. Actual Effective Radiated Power Overlay for two pieces of Equipment

V. REFERENCES

1. Naval Inshore Warfare Communications Analysis. J. M. Horn, P. H. Levine, T. C. Larter, - Technical Document 270 (Vol. 2), Naval Electronics Laboratory Center, 1 September 1973 Unclassified.
2. Required Signal-to-Noise Ratios for HF Communications Systems, H. Akima, G. G. Ax, W. M. Beery, ESSA Tech. Report ERL 131-ITS 92 Aug. 69.
3. Electromagnetic Propagation in a Tropical Environment (U), T. Doeppner, G. Hagn, L. Sturgill, Journal of Defense Research, Volume 4B No. 4, Winter 1972, pp 353-404.
4. Ionospheric Radio Propagation, K. Davies, NBS, April 1965.

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MEASUREMENTS OF 100 kHz LORAN C SIGNAL STRENGTH  
AS A FUNCTION OF VEGETATED SURROUNDINGS

by

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Presented at

Workshop on Radio Systems  
in Forested and/or Vegetated Environments  
US Army Communications Command  
Fort Huachuca, Arizona

6-9 November 1973

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MEASUREMENTS OF 100 kHz LORAN C SIGNAL STRENGTH  
AS A FUNCTION OF VEGETATED SURROUNDINGS

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Abstract

Comparative measurements of 100 kHz E and H field signals were made in various vegetated surroundings on the west coast of Florida near Ft. Meyers. The source was the Loran C Jupiter transmitter located on the east coast of Florida near Miami. Results showed the E field signals to be strongly affected by the vegetation while the H field signals were not. Rough correlation was observed between the E field signal and a qualitative judgment of the vegetation density.

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MEASUREMENTS OF 100 kHz LORAN C SIGNAL STRENGTH  
AS A FUNCTION OF VEGETATED SURROUNDINGS

During December 1970, while making measurements\* of loran "C," 100 kHz, signal strength at various locations on the east coast of the United States, it was observed that the measured field strength appeared to be a function of the local vegetation density. Later it was decided to spend a small effort to investigate this phenomenon further and to see if it affected both the electric and magnetic field components.

The measurements reported herein were taken at various locations near Ft. Meyers on the west coast of Florida. The signal source was the Jupiter loran "C" station at 100 kHz located just north of Miami on the east coast of Florida. The terrain at the receiving site was essentially flat for many miles in every direction.

Several locations were chosen, from one entirely clear of vegetation, to one approaching jungle density. The following chart lists the four vegetated sites used along with an estimate of the density of vegetation. While the estimate is subjective and can be called into question, it is the best that could be done in the limited time available. All the sites were located within a circle with a two mile radius.

The measuring equipment consisted of a high gain amplifier at 100 kHz which could be fed from a vertical tuned whip or a shielded loop antenna. An oscilloscope was used for the readout device since the loran "C" signal is a train of RF pulses. The peak of the pulse was used as an indication of the signal strength. The signal to noise ratio was at least 10 dB at the high attenuation site and greater at the other locations. The tuning of the whip was checked at each location to assure that the nearby vegetation had not detuned it. In all measurements the base of the whip and the center of the loop were four feet above ground.

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\*Measurements were made as part of a DoD funded contract with the Electromagnetics Division, National Bureau of Standards.

QUALITATIVE ESTIMATE OF VEGETATION DENSITY

SITE

- A
  - o PINE TREES ABOUT 3 INCHES TO 5 INCHES DIAMETER, ABOUT 15 FEET APART
  - o NO UNDERGROWTH
- B
  - o LARGE PALM TREES 20 FEET HIGH, ABOUT 10 FEET APART
  - o SLIGHT DECIDUOUS UNDERGROWTH
  - o APPEARED TO BE TWICE AS DENSE AS 'A'
- C
  - o LARGE PALM TREES 20 FEET HIGH, ABOUT 5 FEET APART
  - o MODERATE DECIDUOUS UNDERGROWTH
  - o APPEARED TO BE 3 TIMES AS DENSE AS 'A'
- D
  - o LARGE AND SMALL PALM TREES, ABOUT 5 FEET APART
  - o EXTREMELY HEAVY DECIDUOUS UNDERGROWTH 3 FEET TO 10 FEET HIGH
  - o VISIBILITY LIMITED TO ABOUT 20 FEET IN ANY DIRECTION
  - o APPEARED TO BE 4 TIMES AS DENSE AS 'A'

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-1-A

The loop was used in the vertical plane (horizontal component) and rotated for maximum response. No absolute calibration of the system was made. However, all measurements were made within a few hours of each other and at each site, reference measurements were made in a nearby area clear of vegetation. It is estimated that the relative measurements at each site are correct to within  $\pm 10\%$ , the main uncertainty being in observing the amplitude of the crest of the RF pulse.

Figure 1 shows the relative electric E and magnetic H field signal strengths at the various locations plotted against the estimated density. The readings have been normalized to readings in an area clear of vegetation. The relative signal strength is plotted on a dB or logarithmic scale. Not too much significance should be attached to the fact that the E field observations appear to lie on a straight line because of the subjectivity in the density scale. What is more interesting is the large values of E field reduction, greater than 30 dB, which can occur and the virtual non-reduction of the H field in the same environment.

A theoretical explanation for this behavior of the electromagnetic field components can be found by assuming the air vegetation media can be represented by two isotropic, homogeneous media, and by examining the boundary conditions of this ideal model. This may be a questionable assumption, but for frequencies over which the wavelength is long compared to geometrical dimensions, e.g., tree height much less than wavelength, this assumption may be valid enough to provide a rather clear insight as to whether these measured results should be expected.

The electric and magnetic fields in the two media must match the boundary conditions. The two media are described electrically by  $\mu_0$ ,  $\epsilon_0$ , and  $\sigma_0$  in the air medium and by  $\mu_1$ ,  $\epsilon_1$ , and  $\sigma_1$  in the lossy (forest) medium, where  $\mu$  is the permeability,  $\epsilon$  is the permittivity, and  $\sigma$  is the conductivity.  $E_0$  and  $H_0$  are the field vectors in the air and  $E_1$  and  $H_1$  are the field vectors in the lossy medium, all at the boundary.

In this case,  $H_0$  and  $H_1$  are components tangential to the interface and thus equal.  $E_0$  and  $E_1$  are components normal to the

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interface and thus the two electric displacement vectors  $D_0$  and  $D_1$  must be used to express boundary conditions.  $D_0 = D_1$ ,  $D = \epsilon E$ ,  $\epsilon_0 E_0 = \epsilon_1 E_1$ , but  $\epsilon_0 \neq \epsilon_1$ , and thus  $E_0 \neq E_1$ . Further  $\epsilon_1$  is complex, i.e.,  $\epsilon_{1c} = \epsilon_1 - \frac{i\sigma_1}{\omega}$ , hence

$$E_1/E_0 = \frac{\epsilon_0}{\epsilon_1 - \frac{i\sigma_1}{\omega}}.$$

$\epsilon_0$  is real and of value  $8.85(10)^{-12}$  F/m. A plot of  $\text{dB} = 20 \log_{10}(E_1/E_0)$  versus log frequency is shown in figure 2.

For the frequency range where the magnitude of  $\sigma_1/\omega$  is much greater than  $\epsilon_1$ , the curves show a negative slope of 20 dB per decade, and since  $\epsilon_1$  is not of significant effect, macroscopic values of  $\sigma$  may be measured from  $\sigma = (\epsilon_0 \omega) / 10^{\text{dB}/20}$ , where  $\epsilon_0$  is as defined before,  $\omega$  is  $2\pi$  times the frequency at which the measurement is made, and dB is the dB loss of  $E_1/E_0$  as measured.

Values of  $\sigma$  calculated from our measured values of  $E_1/E_0$  are as follows: - 7 dB gives  $1.2(10)^{-5}$  mhos per meter for site A, -17 dB gives  $3.9(10)^{-5}$  mhos per meter for site B, -23 dB gives  $7.9(10)^{-5}$  mhos per meter for site C, and -32 dB gives  $2.2(10)^{-4}$  mhos per meter for site D.

This is very elementary treatment, but does indicate that the experimental results obtained should be expected. An analysis of a simple surface wave which gives similar results is given by H.M. Barlow and J. Brown, Radio Surface Waves, Chapter II, Oxford at the Clarendon Press, 1962.

An immediate useful conclusion is that for frequencies below about 30 MHz, where H field antennas are practical, the H field may be used in many cases of irregular or heavily vegetated terrain where the E field penetrates relatively poorly.

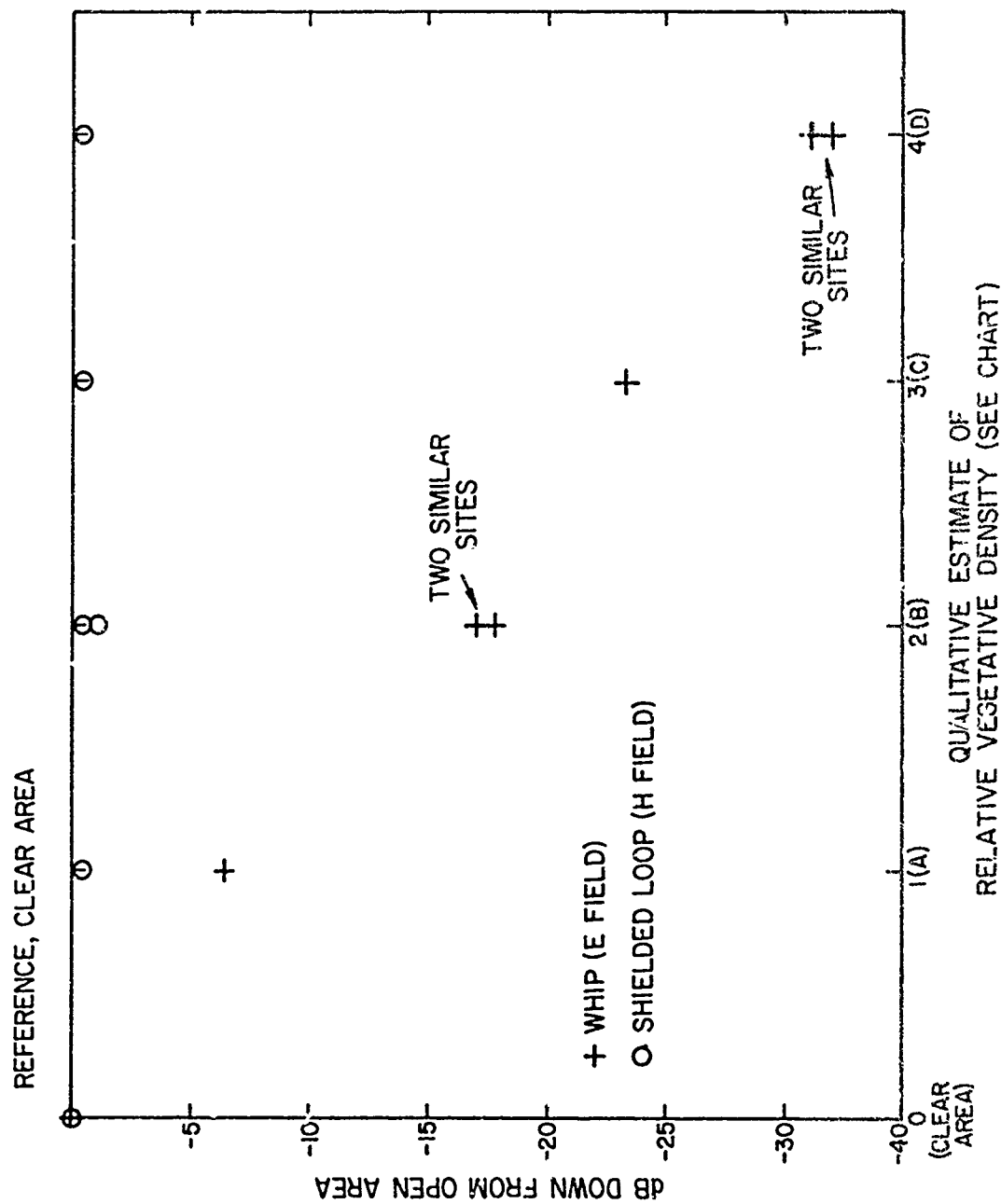


Figure 1.

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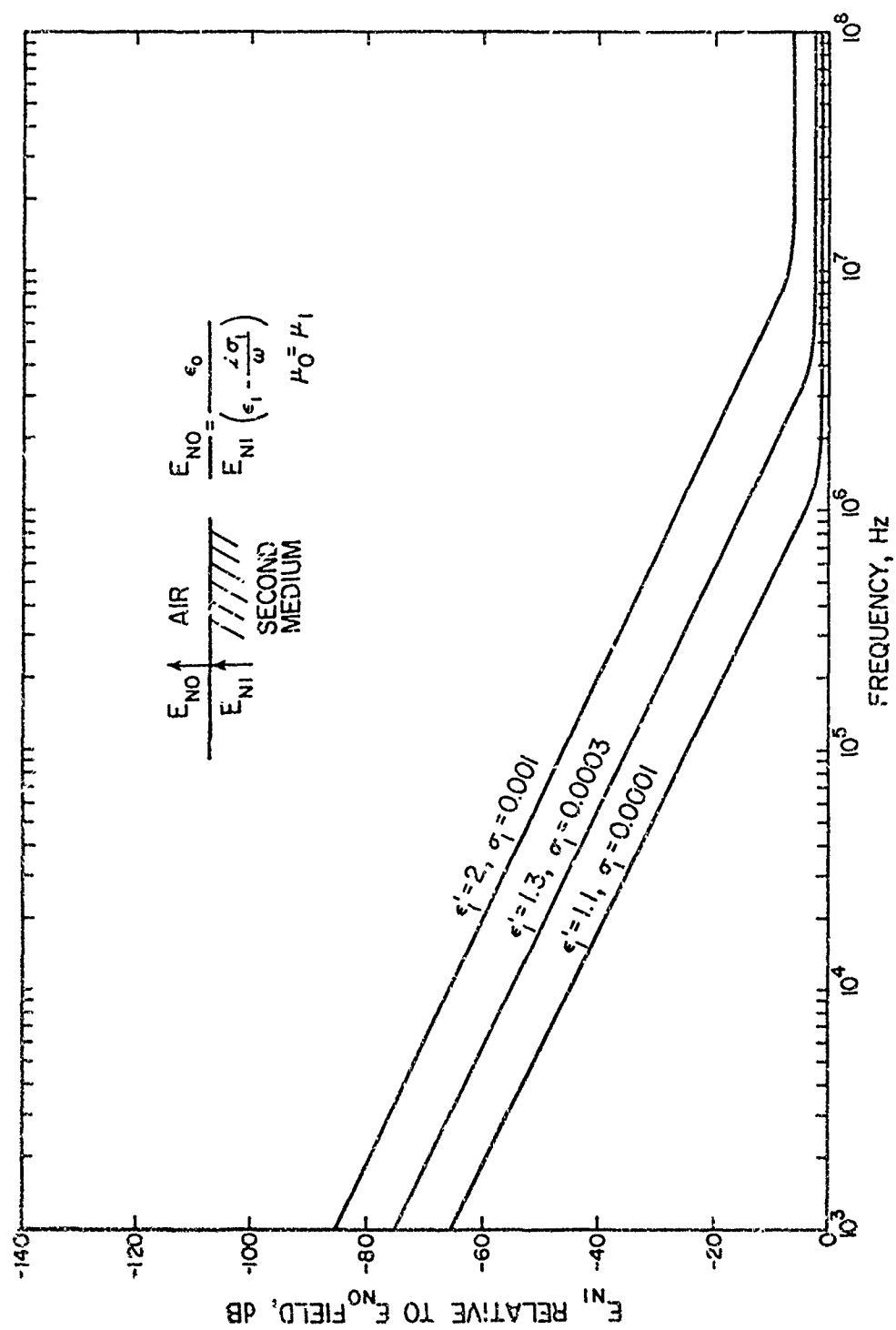


Figure 2.

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CHAPTER II

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## WORKING GROUP DELIBERATIONS - INTRODUCTION

C. W. Bergman, Working Group Chairman

Under the OSD/ARPA Southeast Asia Communications Research (SEACORE) Program, about 20 million dollars was expended to do the research needed to solve the communication/propagation problems peculiar to that area of the world. Much of this effort was focused on obtaining an understanding of radio systems in a tropical jungle environment. Additional effort was also expended in obtaining information concerning the tropical noise environment and the characteristics of the equatorial ionosphere.

It has been a general policy in ARPA to foster exploratory R&D projects to the point where their value was proven and then turn over to one or more military departments the further development and eventual application of such work. In the instance of SEACORE, however, timing and budgetary policy precluded a successful transition of this sort. As a result, despite some initial moves by USAECOM and USACC, one of the program's most important stated objectives (i.e., the application of research and exploratory development to operational hardware and procedures) was never fully realized. Now, five years after completion of the Project, we are failing to fulfill yet another most important objective of the program - that of doing a sufficiently thorough job so that much of the research done will not have to be repeated in the future. Many portions of the data taken have not been analyzed. Some basic data has had to be disposed of, and those who did the research are going into other technical areas and becoming unavailable for utilizing or transferring the valuable experience gained.

Fortunately, USACC has recognized this problem, and as a result, this workshop has been organized to:

1. Apply the results of Project SEACORE and related research to operational problems.
2. Identify needs for further R&D based on the needs of operational radio systems.

In order to accomplish these objectives, USACC has brought together here at Fort Huachuca a number of those scientists who have done the research and those operational people who have related problems. Though simply stated, these objectives will not be easy to realize. It should be kept in mind that in addition to the direct application of the results of the research done, it is also possible to benefit from experience gained by those who did the research and from utilizing laboratory facilities or technical tools developed. There is a great deal to be gained by matching technical talent and research results to operational problems.

The workshop will now break into four working groups to discuss particular problem areas and to make recommendations. The four topic areas are as follows:

1. Application of Antenna and Propagation Theory
2. Spectrum Usage Below 300 MHz (Including UHF Radio 225-400 MHz, but exclusive of Radar)
3. Spectrum Usage Above 300 MHz (Including Radar Above 30 MHz, but exclusive of UHF Radio at 225-400 MHz)
4. Environmental Descriptions (In relation to propagation and system performance modeling)

(The reports of the Working Group Leaders follow. It should be noted that Working Group I met at a different time to allow the members of that group to participate in Working Groups II, III, and IV.)

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## WORKING GROUP I

James R. Wait, Leader

### Application of Antenna and Propagation Theory

The main objective of the working group was to develop a set of recommendations for worthwhile analytical studies. In making such recommendations, it was kept in mind that the ultimate objective is to improve the capability to communicate in difficult terrain.

The members of the working group reached a consensus on most general issues but a number of differences in emphasis emerged. As Working Group I Chairman, I will attempt to summarize these recommendations and points of view. First of all, I will describe briefly the salient points that arose in our discussions.

#### Some General Considerations

(1) The representation of forested covered terrain by a uniform lossy slab with average properties was considered to be a remarkably good model describing transmission at frequencies below about 100 MHz.

(2) The  $1/d^2$  distance dependence followed that expected for a lateral wave in a uniform half-space but the frequency dependence was more complicated. The frequency dependence is  $1/f^2$  if both source and observer are located at the air-slab interface in an asymptotic sense.

(3) The effect of locating obstacles or ridges on the path can be modelled (in a crude sense) by using knife-edges in conjunction with intervening slabs.

(4) The optimum orientation of the antennas was consistent with the excitation of the slab model.

(5) There appeared to be some advantage to using loop antennas for both transmission and reception in special cases.

(6) It was observed that a satisfactory model for microwave propagation over forested terrain should account for the refractive index structure above the tree-tops.

#### Specific Recommendations

(1) That any unused available data (such as available from ITS/OT) that exists for propagation over forested terrain be utilized in an attempt to see if the slab model is applicable to areas other than jungle-type media. Also, secondary features such as cross-polarization and diversity should be examined if they are available.

(2) The physical parameters of the forested media, that are important in specifying the best slab model, should be carefully and comprehensively evaluated. This is important if we wish to predict communication capabilities for inaccessible but interesting regions of the world. In this connection, it would be desirable to re-evaluate the existing propagation data (e.g., from the SEACORE Program) in the light of new analytical models that have been developed.

(3) That an analytical study be made of the inherent averaging process that takes place in the forward scattering of the waves from a lumpy-like medium with uneven boundaries. This is desirable from the standpoint of interpreting localized (in situ) measurements of the medium in terms of the overall transmission problem. In other words, are the locally deduced properties (such as sigma and epsilon) the same as the values to use in the slab model?

(4) That an objective study be made of the capability of the various propagation models to predict observed performance parameters. Limitations and scope of the different methods should also be pinpointed. Where possible, advanced statistical methods should be utilized in order to specify useful bounds on the predictions.

(5) That an effort be made to simplify existing models if they involve complicated computer routines.

(6) That some effort be expended to evaluate hitherto neglected features of the models (e.g., arbitrary profile of the ground surface, variation of mean tree height along the path, and obstacles that are located away from the direct radio path). Available integral equation techniques should be exploited here.

(7) That some attention be given to the mechanism of microwave propagation for line-of-sight paths over and thru forested terrain. For example, can we exploit the possible existence of refractive index ducts over the tree-tops?

(8) That some efforts be made to evaluate the effect of multi-path for transmission in a slab that has deterministic inhomogeneities of a specified form. Such a study would facilitate the interpretation of any pulse on time-domain that are available.

(9) That a very comprehensive survey be made of the relative merits of different antenna types that would be used to excite lateral waves in forested terrain. The main goal of such a study would be a set of specifications and guidelines on the expected performance and operation of each antenna type.

LIST OF ATTENDEES - GROUP I  
8 NOVEMBER - PM SESSION

<u>NAME</u>	<u>AFFILIATION</u>
C. W. Bergman	Defense Communications Agency Defense Comm. Engr. Center Reston, VA
Robert Bevensee	Lawrence Livermore Labs Livermore, CA
Dr. Harold T. Dougherty	Institute for Telecommunication Sciences Boulder, CO
Dr. Donald G. Dudley	University of Arizona Dept. of E. E. Tucson, AZ
Dr. Carl L. Frederick	Southwest Research Institute San Antonio, TX
George Hufford	Institute for Telecommunication Sciences Boulder, CO
Dr. Paul Levine	MEGATEK Corporation San Diego, CA
Mark T. Ma	Institute for Telecommunication Sciences Boulder, CO
Dr. Randolph H. Ott	Institute for Telecommunication Sciences Boulder, CO
Dr. David L. Sachs	Science Applications, Inc. LaJolla, CA
Dr. Leon Steinert	Lockheed Electronics Co. Tucson, AZ
Dr. Theodor Tamir	Polytechnic Institute of NY Brooklyn, NY
Harold Tolles	USACEEIA Fort Huachuca, AZ
Dr. James R. Wait (Chairman)	Institute for Telecommunication Sciences, ERL/NOAA Boulder, CO

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WORKING GROUP II - SPECTRUM USAGE BELOW 300 MHz  
(Including VHF Radio 225-400 MHz, but exclusive of Radar)

Robert A. Kulinyi  
Leader

1. The Working Group met as shown in the official Agenda with a membership substantially as forecast by the sign-up sheet posted at the general workshop session. A total of 20 individuals attended the two open sessions, of which 16 were at both. See the attendance list attached to this report. In addition to presentations noted below, written material was provided to the Group Leader by three attendees. These are reflected in the text to follow as discussion items or recommendations

Special appreciation must be expressed to Morris Acker of ECOM and Gary Barker of SRI for their assistance in preparing the text of recommendations and material for presentation at the final Workshop session - an endeavor which extended past midnight of 8 Nov.

2. Presentations of specialized interest for Group II were given as noted here. The first two were early on 7 Nov in the Group meeting and the third was mid-way in the morning session of 8 Nov.

a. "A Novel Graphical Technique for Spectrum Utilization/Communications Planning" by P.H. Levine and T.C. Larter of Megatek Corp., Harbor City, CA; and J.M. Horn of Naval Electronics Laboratory Center, San Diego, CA.

b. "A Communication Channel Simulator for Forested and Vegetated Environments" by Morris Acker. US Army Electronics Command, Fort Monmouth, N.J.

c. Mr. Sol Perlman, US Army Electronics Command, Fort Monmouth, N.J. presented material on avionics problem areas in Nap-of-the-Earth Communications and US Army Aircraft antenna gain and pattern variations.

3. Discussions on Group II Agenda Items

a. Propagation Mechanisms

(1). At lower frequencies it was observed that the E-field was attenuated at greater rates than the H-field. At higher frequencies no observations were cited, hence a need for more data was expressed.

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(2). Discussion led to a conclusion that better means for coupling antennas to the forested and vegetated media were needed. Possible optimization of lateral wave launching was discussed and it was decided that, so far as was known, simple antennas provided the best means for this.

b. Prediction Methods

(1). HF Ionospheric techniques were briefly reviewed, noting the novelty of approaches such as that of paragraph 2a, while the need to consider limitations of any abbreviated method was also apparent. Two other techniques were discussed: the CURTS system of Stanford Research Institute developed for DCA and the in-house efforts at ECOM on Near-Real-Time Ionospheric Sounding and Prediction for Field Army Distances.

(2). Considering a broader frequency range, there was agreement on the need for better models for transmission predictions. These would lead to higher reliability in overall system design when EM propagation in difficult environments was an important concern.

(3). It was noted in the group discussion on Mr. Acker's paper (Paragraph 2b above) that this technique of multipath simulation needed the provision of path tapes taken in forest areas. In this way more costly extended or repeated equipment tests in those areas would be minimized or eliminated.

c. Multipath Effects

(1). A primary concern here was the movement towards digital transmission in most frequency ranges. It was noted, despite presentations at the general workshop sessions, that insufficient data was available on multipath in vegetated and urban areas to yield fully useful predictions of system error rates. Specific instances discussed were those of sensor communication links and spread spectrum modulation techniques at VHF.

(2). Some group attendees noted multipath effects led to depolarization of signals and questioned whether cross polarized antennas would provide diversity gain in a forest with high trees. There appeared to be insufficient data in this area.

d. Signal-to-Interference Ratio

(1). Noise was noted as one of the most difficult types of interference to overcome in vegetated environments,

primarily due to a lack of consistent data suitable for detailed prediction of system impact. While there have been some observations of differences in signal-to-noise ratio in-vs-out of the jungle, this relationship is not fully established. Measuring techniques for natural and man-made noise are not sufficiently correlatable from user to user, particularly when dealing with man-made noise.

(2). A need was cited for more knowledge on antenna directivity in forested areas. Given available data, there appear to be applications for steerable-null array techniques to yield improvements against some types of interference.

e. Antenna Relationships

(1). In many applications, electrically short radiators are unavoidable, such as sensor data-links and squad radios. There is insufficient design data which reflects the impact of vegetation parameters on these antennas.

(2). There appears to be a general lack of consideration for antenna study and modeling in relation to system constraints in the early design stages. More data from SEACORE antenna testing should be provided to development and engineering users.

f. Practical Considerations

Discussion centered on how to better disseminate the data already available from SEACORE and other studies in forested and vegetated regions. A translation of the many research papers, test reports and other technical data into training material suitable for adding to or replacing that now used in military school systems appears necessary. Texts, including handbooks, may be configured from presently available inputs to meet these needs.

4. Other Group II Discussion Items

a. A possible new application of ground reflectometry techniques was presented by Mr. J. Adams, NBS at Boulder, CO, for potential use in forest and vegetation characterization. This might utilize either reflectometry or transmission measurements. NBS has developed an experimental, van mounted facility for this.

b. Various suggestions were made for added capabilities for antenna modeling of a physical and analytic nature to better predict effects of forested, vegetated and urban environments on EM signals.

## 5. Group II Recommendations

### a. Propagation Mechanisms

(1). Additional tests and studies are needed to better relate short term statistical variations to long term signal characteristics in the various media traversed; this should be further extended to include effects of ground and vegetation parameters. For frequencies below 3 MHz, navigation systems need special attention to characterize effects on phase and timing due to media variability.

(2). Measurement techniques and systems are needed to determine effects of the environment on the propagation path. The long and short term variability of factors affecting amplitude and phase on paths in forested, other vegetated and urban areas as a function of frequency will be considered.

### b. Prediction Methods

(1). Information derived from the measurements of path variability should be developed into empirical statistical estimators for incorporation into transmission models. These statistics should be used to define probability of successful system performance.

(2). Techniques providing a higher level of near-real time ionospheric prediction capability should be developed. These will allow improved frequency management over both long and short distance circuits and will supplement existing long term prediction models.

(3). Existing transmission channel simulation capabilities should be extended to include UHF and higher frequencies with increased channel bandwidths to accommodate newly designed digital systems. The channel simulator tape library should be extended to encompass a more complete range of environmental parameters.

### c. Multipath Effects on Digital and Analog Signals

(1). More data on multipath effects related to environmental factors are needed for wideband digital, spread-spectrum and analog signals. Trade-off studies are needed to conserve spectrum usage while achieving system objectives in the presence of multipath effects.

(2). Other-than-linear antenna polarization capabilities to overcome certain multipath effects in urban and forested environments should be studied and tested.

d. Signal to Interference Ratio

(1). Measurements of man-made and atmospheric noise should be extended to determine both long and short term variations. This should serve to establish both specific and detailed descriptions of noise in forested, vegetated and urban areas.

(2). The application of directive and steerable-null antennas should be investigated for radio systems in forested, vegetated and urban areas.

(3). Observations of differing attenuation of signals and noise in forest media indicate a need for further investigation of noise propagation mechanisms and paths relative to the signal propagation paths.

e. Antenna Relationships

(1). Information and data on antenna performance in forested environments, obtained in the SEACORE Program, must be summarized and distributed to operational personnel and equipment designers.

(2). There is a need to establish the operational feasibility of efficiently coupling antennas to natural propagation modes existing in forest and vegetated media.

(3). More statistics are required on the effects of various types of forests and vegetation on antenna gains, impedance and coupling to propagation paths.

(4). Suitable reference antennas are required to evaluate the relative performance of existing and proposed antennas. This is especially important when such antennas are to be mounted on or near complex structures.

f. Practical Considerations

Information obtained under SEACORE and similar programs describing environmental effects on radio systems must be configured as, or incorporated into engineering texts, training manuals, handbooks and operations manuals. Some immediate uses of such data can be achieved. Instances of these are:

(1). Application of dipole height gain data to improve performance of HF radio circuits at near vertical incidence.

(2). Use of horizontal polarization at HF and the lower VLF to improve transmission within tropical forested areas.

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## REPORT OF WORKING GROUP III\*

Spectrum Usage Above 300 MHz  
(Including Radar Above 30 MHz but  
Exclusive of UHF Radio at 225-400 MHz)

### 1.0 INTRODUCTION

Working Group III adopted the objectives of (1) identifying applicable results obtained from Project SEACORE and associated programs, and (2) determining areas needing additional research for purposes of satisfying tactical operational needs. The two general sessions were focused on identifying specific operational problems and uncertainties experienced in the operation of a number of systems in or near foliated environments, identifying problems likely to be encountered in operation of future systems in such environments and what is needed to resolve and/or avoid such problems.

The following section identifies a number of the systems operating in the subject frequency range and the associated needs discussed by the Working Group.

### 2.0 SOME RF SYSTEMS AND ASSOCIATED OPERATIONAL NEEDS

A number of tactical systems in foliated environments in the subject frequency range were discussed. These are summarized below with emphasis on the operational aspects.

#### 2.1 FOLIAGE PENETRATION RADAR

Radars considered here are MTI systems intended to detect moving targets in vegetation.

Land Warfare Laboratory has developed short range man-transportable systems at 140 MHz and at 1300 MHz. One 140 MHz system was designed to be effective as an intrusion detector, to detect the presence of walking men. Another 140 MHz system was designed to detect low flying helicopters which are obscured by foliage.

Lincoln Laboratory and Harry Diamond Laboratories evolved a larger transportable 435 MHz system which is an effective intrusion detector at longer ranges. This latter has become known as the Camp Sentinel Radar.<sup>1</sup>

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\* Prepared by Panel Members: Lincoln Cartledge, John Hicks (Leader), George Kizer, Sol Perlman, and Lewis Surgent. The panel wishes to thank the Working Group participants for their valuable contributions.

Airborne foliage penetration radars include a 900 MHz helicopter-borne "Airborne Truck Detector" and a lower frequency noncoherent radar which was tested on a C-47.

We are aware of some work by USAECOM on a small portable system operating near 200 MHz.

All of these systems are essentially prototypes. Only one or a few systems of each type have been built and operational experience has been limited to service test levels. Hence, detailed listings of user problems are not yet available. Note, however, that the development of all these systems was largely motivated by the inability of existing X- and K-band Doppler radars to penetrate foliage.

As their name implies, foliage penetration radars propagate signals over paths which go partly or wholly through vegetation. The smaller man-transportable systems operate with both the radar antenna and target below the treetops. Camp Sentinel Radars are designed to operate with antennas above the treetops. Hence, the important propagation modes include line-of-sight through vegetation, lateral wave and a combination of free space and diffraction into the vegetation.

Obviously, prediction of a radar's performance requires knowledge of the path loss from radar to target. A considerable data base relative to this path loss exists?

The lateral wave model is used with some success for the simple situation. In many cases, however, foliage penetration radars are to work in forested areas which contain cleared areas as well. Signal strength prediction along these "mixed paths" is more complicated. Several methods of attacking this mixed path problem are discussed in reference 3.

The foliage penetration radars are MTI radars; i.e., they make detection by recognizing the Doppler shift associated with moving target echoes. Prediction of MTI performance involves, in addition to the path loss, prediction of the relative strength and spectral characteristics of both the clutter and target return. Likewise, design of optimal MTI radar systems depends on prediction of the strength and Doppler spectrum of both targets and clutter echoes.

At the frequencies of interest the vegetation can be modeled as a lossy dielectric slab with random spatial variations of the complex index of refraction. Such a slab demands a statistical description. Our ability to design systems and to predict performance is limited by our limited ability to accurately predict the statistical parameters of the spatial distribution of the dielectric constant.

Foliage penetration radars are intended to detect walking men or moving vehicles. These targets are on the ground; hence, ground lobing effects are important. Signal strength will usually

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be near zero at the electrical ground level and vary more or less periodically with increasing height.<sup>4</sup> The height at the first periodic maximum is a function of the forest parameters and of the radar frequency. It increases as the frequency decreases; i.e., at low heights ground lobing causes reductions in signal strength as the frequency decreases. Conversely, the attenuation in the foliage decreases as the frequency decreases. These two counteracting effects suggest the existence of an optimum radar frequency for any given forest environment.

Other multipath phenomena are important. Forests, particularly near the ground where the targets are located, consist of large scatterers, which are spaced many wavelengths apart at VHF. Reflections from these scatterers give rise to multiple propagation paths which, in turn, have the effect of adding spurious modulation to the target echoes. When wind moves the trees, the multipath structure becomes time varying and the nominally zero Doppler clutter returns are modulated. The resulting sidebands limit the radar's ability to detect slow moving targets.

In the process of developing foliage penetration radars, both LWL and Lincoln Laboratory found it necessary to make theoretical and experimental studies of propagation phenomena in vegetation.<sup>5, 6, 7, 8, 9, 10</sup> These have led to a fairly good qualitative understanding but quantitative information suitable for predicting radar performance is still largely lacking. In particular, we need an adequate data base so that the parameters of the volume distributions of dielectric constant and loss tangent can be derived from the biological and topographical descriptions of the forest.

Parameters of interest include the mean, variance and two-point correlation function of the complex dielectric constant as well as the variation of these parameters with time.

## 2.2 LINE-OF-SIGHT AND TROPOSCATTER COMMUNICATION LINKS

Present tactical microwave communication equipments operate primarily in the 750 to 950 MHz and 4 to 8 GHz regions with adoption of 14 GHz systems expected as well as system developments to 35 GHz or so. Communication links are often established between clearings separated by vegetated regions and from clearings into vegetated regions. Intervening paths may be mixed vegetation-clearing. Some links have one terminal elevated as typical when a line-of-sight link communicates with a troposcatter relay on a mountain.

The establishment of such communication links in tactical situations is often complicated by other operational requirements and inadequate guidelines to meet the unusual siting problems. For example, shelters, vehicles, helicopter landing areas and the like may heavily influence terminal locations. Sometimes the nearby topographic features are altered after antenna installation such that the original siting criteria and performance are altered. Tree tops may be in the main beam or sidelobes, possibly a result of

natural growth after installation in some instances for fixed paths and possibly due to concealment factors. Cutting the trees may not be permitted. At present most of the systems appear to operate at voice bandwidths but some are PCM with signal bandwidths of 4 to 5 MHz. Increasing use of digital communications for security and other purposes is expected to bring greater bandwidths.

Current problems of major concern appear to be severe fading due to atmospheric phenomena, extending the operating range with present power and how to treat the problems of trees near the antennas and within the path in general. Questions were posed as to whether narrower beams could be used to increase range and what the effects of the trees are in general and particularly in terms of beam alignment and in future applications related to message errors over PCM links. Space diversity is currently employed to combat the atmospheric fading and may be useful in applications where the antennas are near the forest-air interface. The spatial correlation distance required to combat fading caused by trees swaying with the wind, however, is not known at these frequencies. Propagation mechanisms are usually line-of-sight, diffraction, the lateral wave and troposcatter. Some questions were also posed as to the effects of atmospheric refractivity index gradients associated with forested regions. For operating frequencies approaching 1 GHz and higher, the well known effects of the atmospheric refracting structure upon microwave propagation can constitute a propagation problem in addition to those usually associated with propagation in wooded areas. For example, sparse refractivity measurements demonstrate that strongly negative refractivity (ducting) gradients can occur at times just above tropical jungle canopy; similar structures have been reported from Swedish forests. These refractivity structures are dependent upon the variations of the temperature and humidity of the air with height, horizontal displacement and time. Further, marked differences in the atmospheric refractivity structure (variation of refractivity with height) have been observed below the canopy (treetop) heights between clearings and within the jungle.<sup>11, 12, 13</sup> This effect of these structures in the vicinity of 1 GHz can complicate the problem of interpreting experimental data for both terrestrial point-to-point and ground-to-air applications.

Elevating the antennas above the foliage where possible is a general and well known solution to many of the above problems. It is suggested that a partial solution to some of the operational problems of raising antennas to treetop height and above is to use elevated passive reflectors rather than elevate the active structure with its feedlines. These are discussed in the open literature with the use of passive reflectors being well treated in the Japanese literature.

A number of the practical questions posed may be addressed by application of SEACORE and related work, particularly those related to attenuation through the foliage and communications performance in general.<sup>14, 15, 16</sup> The questions regarding precise prediction at these frequencies for the antennas operating near the

rough surface of the treetops, however, are unanswered. A theoretical solution for this case has apparently not been developed. It would be particularly useful in terms of predicting the signal variance.

### 2.3 TACTICAL NAVIGATIONAL SYSTEMS AND AIRCRAFT LANDING AIDS

An ILS radio signal source at K-band for a helicopter landing system in a tactical environment with terrain covered by grasses and low bushes can be distorted by depolarization, multipaths and absorption. The helicopter approaches the runway at about an 8 degree elevation angle. Data are needed to determine the accuracy of the landing approach starting about 1 to 2 miles away from touchdown.

A navigational satellite system applied to aircraft in flight over a forested area will be affected by multipaths. The signal frequency for such a system is proposed to be about 1600 MHz. The satellite signal arrives at elevation angles between 10 to 60 degrees, depending on latitude and subsatellite position. Will signal scattering and absorption minimize the multipathing over a vegetation covered surface compared with earth or water surfaces?

The TACAN system must often be placed in small clearings surrounded by forests and other obstacles. The scattering and multipaths may cause the system to be unusable at some azimuths. The a priori performance is not predictable and several hours of test and evaluation during installation may be required. A performance prediction method would be of value.

### 2.4 VEHICLE AND PERSONNEL POSITION LOCATING SYSTEMS

A Marine Corps Position Locating and Reporting System for operation in the 400 MHz range is under development. Its operation will utilize trilateration and/or precise timing techniques. The required bandwidth of the system is about 10 MHz. Multipath environments impose limitations on usable bandwidth and at present these are not well known for wooded areas. Some pertinent results on bandwidth limitations and multipath phenomena in forested environments are available from Project SEACORE in the VHF and UHF frequency range,<sup>17</sup> but more experimental data are needed to define the multipaths in general wooded areas. Propagation prediction techniques for forested and vegetated environments would also be an asset in general.

## 3.0 CONCLUSIONS AND RECOMMENDATIONS

The discussions made it clear that there is a gap between the user and research communities regarding radio frequency propagation in forested and/or vegetated environments at the frequencies of interest to this Working Group. The research effort has been somewhat general and less extensive than at the lower frequencies.

These efforts, however, have produced an awareness and qualitative understanding of factors that influence propagation at these frequencies in such environments, but the results are generally contained in detailed research reports rather than application documents.

The following recommendations are aimed at making maximum use of existing data and knowledge and of research efforts for advancing the knowledge in areas of primary importance to tactical applications.

1. The slab model of forested environments is applicable for estimating the median path loss for systems up to frequencies of 1 GHz or so. It should be interpreted in its most practical terms and made available for use by operational personnel.

2. Operational problems should be more thoroughly identified in terms common to both the research engineer and users and a document encompassing known solutions, qualitative approaches and guidelines developed specifically for use by operational personnel.

3. A document utilizing current knowledge on radio system performance and prediction techniques in vegetated environments should be prepared for use by system designers and those responsible for generation of system requirements. For example, design envelopes in terms of antennas, antenna heights, frequency, power, etc. would be typical content.

4. Further analysis of existing data bases and further experimental work are needed at frequencies above 300 MHz. These efforts should focus on such factors as the electrical parameters of the forest, multipath effects, two-point correlation functions, backscatter cross section of the vegetation, Doppler spectra and others and their integration into a model for prediction purposes.

5. Development and/or exploitation of mixed path models is needed for predicting the detection range of foliage penetration radar and communication performance in general.

6. A theoretical treatment of scattering by the rough air-foilage interface that serves to bound the random foliated medium when the antennas are placed near the boundary is needed, particularly for communications performance predictions.

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## WORKING GROUP IV: ENVIRONMENTAL DESCRIPTIONS

G. H. HAGN, WORKING GROUP LEADER

### 1.0 PREFACE

To put the efforts of Working Group IV (WG IV) into perspective, it should be noted that this group was planned to provide support to WGs II and III on operational problems in forested areas and WG I on analytical modeling. Its primary goal was to determine the types and formats for environmental data required to solve operational and analytical problems and to identify data already available for this purpose -- as well as voids in our current knowledge. I would like to thank the people who worked in this group on the two days (see Appendix A), especially those who provided written inputs: Adams, Button, Ikrahn, Kitchen, Lane, Lytle, McLeod, and Robertson (who could not attend). I especially want to thank Dr. McLeod for acting as recording secretary and Drs. Kitchen and McLeod for working with me after the conclusion of the group sessions to put together the first rough draft of this report for presentation at the Workshop. The references at the end are by no means comprehensive. Finally, any errors of commission or omission are solely mine.

### 2.0 INTRODUCTION

This working group addressed the problem of describing the forest environment in operationally descriptive terms as well as in engineering and scientific terms. It was the group consensus that environmental classification was the most important topic and three engineering and scientific categories were defined:

- The physical environment (the type of environment one can see).
- The electrophysical environment (the electrical properties of soil, vegetation and the atmosphere).
- The electromagnetic wave environment (the environment of radio energy, including radio signals and noise).

It was concluded that the reasons for classification of the environment must be specified in order to determine the appropriate classification techniques. The following Department of Defense (DOD) reasons for environmental classification were identified: 1) To facilitate the provision of guidance to field operators in the form of handbooks and other aids. (For example, guidance on how close to a tree trunk an operator can place his antenna without seriously degrading the performance of his radio system); 2) To facilitate the

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use of radio systems performance models in computer war gaming; 3) To facilitate planning field test exercises and actual military operations; 4) To provide documentation of the environment during the performance of tests and evaluations (including the calibration of test ranges); 5) To provide input to the process of radio systems design; 6) To provide documentation when radio propagation and antenna models as well as radio noise and interference models are being field checked prior to their use in radio systems performance models. Other DOD reasons for environmental classifications exist (e.g., to validate studies of mobility, etc.) but the foregoing list is intended to relate directly to radio systems. Valid non-DOD classification requirements exist also (e.g., scientific descriptions relevant to the study of the environment by botanists, aids to forest management, environmental control, etc.), but these were not of primary concern to WG IV.

The following discussion will begin with a listing of the types of environmental classification techniques and their relationship to military scenarios and to mathematical models of antennas, propagation, and radio system performance. While noise, interference and susceptibility also are important, they are treated in less detail. Model input data and parameter sensitivity are discussed. The relationships between the physical and the electrophysical environmental properties are reviewed as they pertain to extrapolation to other locations, other radio frequencies, etc. Variations in available model input data are discussed as well as the need for procedures required to use the models in the absence of some of the required input data. Measurement techniques and their limitations are discussed. Conclusions and recommendations are given regarding making the best use of existing information as well as for future R & D work.

### 3.0 DIMENSIONS OF ENVIRONMENTAL CATEGORIES

#### 3.1 Operationally Descriptive Categories

In general, military scenarios are couched in a geopolitical frame of reference, whereas evaluation of performance of radio systems used to support military operations requires the use of an engineering and scientific frame of reference. Hence, it is necessary to relate these two contexts to do the analyses required. In simple terms, this involved the process of going from a map of a region that has geopolitical significance to a description of the physical, electrophysical and electromagnetic environments in that region in terms of parameters that can be used to run models to predict the performance of radio systems as a function of tactically meaningful variables such as communication range, reliability, etc. For example, in the requirements study for tactical radios planned for use in the 1980 time frame (Tactical Radio Communication Systems, TRCS), 13 DOD-generated scenarios were employed and the world was divided into 10 regions (e.g., Northern Europe, Southeast Asia, etc.).<sup>1</sup> Within each region, any given location was assigned to one of 7 soil types, 8 terrain types,

9 climates and 10 vegetation types. Electrophysical values were assigned to each of the soil and vegetation types, etc., for use in radio propagation analyses. More detailed classification systems have been devised for geopolitical subregions. Vietnam, a subregion of SEA, was analyzed, and 17 different vegetation descriptors (including bare earth) were generated and related physically and electrophysically to a map of Vietnam.<sup>2</sup>

### 3.2 Engineering and Scientific Descriptive Categories

#### 3.2.1 Dimensions of the Physical Environment

##### 3.2.1.1 Geography

Various systems are employed by geographers. Some of these are described in Ref. 3.

##### 3.2.1.2 Topography

Topography has been described as a function of terrain type, and considerable conversion of actual terrain elevation data into a computer-usable form (digitized data) has been accomplished by the DOD.<sup>4</sup> A variety of terrain types (e.g., smooth plains, rugged mountains, etc.) have been defined. For example, eight types of terrain irregularity (as described by the interdecile range) have been related to these terrain types.<sup>1</sup>

##### 3.2.1.3 Geology

The earth has been mapped on a global basis in terms of geological formations, and some work has been accomplished on making maps of earth electrical parameters.<sup>5, 6</sup> It is important to distinguish between surface electrical values of soils and the values pertaining to the underlying formations -- as well as between true and effective or "apparent" values.<sup>7</sup>

##### 3.2.1.4 Climatology

The primary climatological variables related to radiowave propagation include temperature, atmospheric pressure, humidity and liquid water content, rainfall rate at the earth's surface, average rainfall over a year, and prevailing winds, etc. These variables relate to propagation through the surface refractive index of the atmosphere and the scale height, which have been mapped on a worldwide basis, and through the scatter from (and attenuation by) rain.<sup>8</sup>

##### 3.2.1.5 Vegetation

A variety of systems have been developed for classifying vegetation,<sup>9</sup> and biogeographers have mapped the occurrence of the various types.<sup>10-12</sup> L.R. Holdridge<sup>13</sup> has developed a system for classifying vegetation that relates humidity and mean annual bio-temperature to

types of vegetation. He has categorized the world life zones and plant formations into twelve humidity provinces and six temperature regimes and related these regimes to latitudinal regions ranging from tropical to polar and altitudinal belts ranging from sea level to nival. His classification system for mature natural forest stands (where no strongly restrictive growth factors are present) has proven effective in the tropics for predicting the types of vegetation which will be most likely to occur as a function of humidity and temperature.<sup>14</sup> It can be used to supplement other methods of predicting vegetation types in areas where no direct access is available.

### 3.2.2 Dimensions of the Electrophysical Environment

The primary dimensions of the electrophysical part of the forest environment are the macroscopic electrical properties (complex dielectric constant) of the ground, forest and the air above the forest. Some relationships between these parameters and the physical environment are discussed later.

### 3.2.3 Dimensions of the Electromagnetic Wave Environment

The primary dimension of the radio frequency spectrum is frequency (or wavelength). The International Telecommunication Union has defined the radio frequency spectrum by band, and has specified by international agreement what types of uses these bands and sub-bands may have.<sup>15</sup> In addition to signals, there are several varieties of noise which occupy the radio frequency spectrum. Atmospheric radio noise has been classified on a worldwide basis as a function of season, time of day, and radio frequency.<sup>16</sup> Cosmic noise and solar radio noise have been discussed by numerous authors.<sup>17</sup> Man-made radio noise is less well documented, although Disney,<sup>18</sup> Skomal<sup>19</sup> and others have presented possible methods of relating man-made noise to the environment producing it. Man-made radio noise of an intentional nature includes those devices used in electronic warfare (jammers, spoofers, etc.).

## 4.0 LIMITATIONS AND APPROACHES

### 4.1 Limitations on WG IV Discussions

The environments dimensioned in the preceding section are very broad. To facilitate discussions, the WG IV attendees put several bounds on subsequent discussions. The frequency range of interest extended up to 15 GHz. Potential applications of environmental descriptions concentrated on the timeframe out to 1980. The dimensions of the physical environment based on military scenarios were limited to 1000km or less, and the concept of an operational volume was found useful. The engineering and scientific volume(s) of interest include a cubic wavelength at the radio frequency under consideration, etc.

## 4.2 Philosophical Approaches

Two philosophical approaches to environmental description were explored: scientific and operational. The scientific approach consisted of going back to first principles (Maxwell's equations) and describing the environment in a way that enables the solution of the equations with the required accuracy. It was observed that knowledge of the environment near the end points of a propagation path is more important than a detailed knowledge of the middle. Hence, it is possible to sort the problem into two parts: coupling to (and from) the medium, and propagation through it. This can be re-phrased as the problem of determining the self impedance of transmitting and receiving antennas, and determining their mutual impedance.

The operational approach is essentially a baseline approach. Here one would build on the existing systems for environmental classification. One could relate the parameters of these existing systems to the ones needed to run analytical radio system performance models. Alternatively, one could use a purely empirical approach and use the performance of actual military equipment to classify environments where operational experience had been obtained.

It was concluded that both approaches had merit, and that a composite approach should be employed, with emphasis on the baseline.

## 5.0 SCENARIOS AND MATHEMATICAL MODELING

No standardized method exists for proceeding from the types of environmental descriptions used in military scenarios to the performance of radio systems used in those scenarios as a function of range, antenna height, etc. However, several examples of this type of work have been mentioned.<sup>1, 2</sup> A variety of models exist for the performance of antennas, for radio propagation, noise and interference and the performance of radio systems in a variety of environments (see also the papers section of these proceedings). It was beyond the scope of this workshop to generate a composite current list of these models and their availability, the environmental input required, the outputs produced, and their accuracy and limitation. These models can be run for a given type of communication system as a function of frequency, range, etc., as germane to military scenarios, and the system performance predictions are useful for the variety of DOD reasons for categorizing the environment discussed in Section 2. At present, however, very little guidance is available to the engineer attempting to relate scenarios for a forested area to the available analytical models.

## 6.0 MODEL PARAMETER SENSITIVITY

It is very important to identify the significant environmental parameters, namely the parameters which the models indicate have a significant impact on system performance. One way of identifying

these parameters for a given model is to run the model for a range of values of the input parameters and note those parameters which produce particularly significant effects on the model outputs. For example, the forest slab model developed by Taylor<sup>20</sup> was used in this manner and it was concluded that for determining the gain toward the zenith of a horizontal dipole antenna in the forest, that the height of the antenna above the ground was the only truly significant parameter -- the same conclusion as in the absence of vegetation. Similarly, Sachs<sup>21</sup> concluded that the conductivity of the forest slab was the most important parameter in determining basic transmission loss for ground-to-ground communications in a forested area. Another parameter of importance for antennas situated in irregular terrain is the effective height<sup>22</sup> of the antenna defined relative to the surrounding terrain. A study of the parametric sensitivity of the environmental input data required for propagation and antenna models is an important source of guidance for the specification of the accuracy required for the input data.

## 7.0 ELECTROPHYSICAL MODEL INPUT DATA

### 7.1 Ground Electrical Parameters

Let us now consider model input data availability. The electrical properties of the ground are required in most antenna and propagation models. These parameters are known to be a function of radio frequency but current practice<sup>22</sup> usually involves using values developed for use at frequencies around 1 MHz as listed in various radio handbooks<sup>23</sup> and related environmental descriptions by very general soil type (sandy, pastoral, etc.). Usually, measured values of electrical ground constants for the location and frequency of interest are not available, although some data of this type does exist.<sup>24, 25</sup> It should be noted that when empirical data have been used to modify theoretical models for a given type of terrain, it is important to use the same electrical constants in subsequent uses of that model even though they do not match the physical-electrical constants which exist at the site. This same comment applies to models for propagation in forests with respect to the forest electrical properties. It should be noted, however, that it is preferable to use the best available information on electrical constants of ground and vegetation prior to any empirical modification.

### 7.2 Vegetation Electrical Parameters

Values for the electrical properties of forests have been obtained using several techniques as discussed by Hagn.<sup>26</sup> Values for the dielectric constant and conductivity of the forest are useful descriptors of a forest as a lossy dielectric slab for frequencies below approximately 500 MHz. Estimates of these parameters have been obtained using open-wire transmission lines in the frequency range 6-75 MHz.<sup>25-28</sup> At higher frequencies, curve fitting of measured antenna pattern data<sup>29</sup> has proven effective for estimating these parameters. At LF, a technique has been proposed by Reeve and Adams which appears promising that involves the use of measurements of the wave impedance in air and in

the forest.<sup>30</sup> The effective forest height is a parameter required for use in the slab models. It is possible to fit measured propagation loss data to slab model predictions and to adjust the parameters of the ground and forest slabs to obtain a fit. This approach does not provide unique electrical properties in the same sense as the open-wire line and wave-impedance techniques mentioned above, but it does give parameters that are useful in running the models for the exact terrain where the measured data were obtained. There is, however, a problem in extrapolating to other geographic locations (e.g., Thailand to Panama)<sup>31</sup> and also in extrapolating to other frequencies.

### 7.3 Relationship Between Vegetation Physical and Electrophysical Properties

It is important to try to relate the electrophysical properties required in propagation models to physical properties of the forest environment which can be measured. Several attempts have been made to relate forest electrical properties to biomass (tons per acre) of vegetation in a given area and to biodensity (pounds per cubic foot). Foresters have developed relationships between Breast Height Diameter (BHD) and biomass.<sup>32</sup> Other relationships have been developed empirically between BHD and tree height. Hence, one can compute biomass for an area from the number of trees and their BHD's and convert to biodensity by dividing biomass by some measure of effective tree height. The spacing of trees as expressed in terms of nearest neighbor distance (NND) is another parameter that has been found to be useful in relating physical properties of forests to radio propagation effects. The radio frequency at which the pattern of a vertical whip antenna in a forest starts to develop significant lobing in azimuth can be related to NND.<sup>33</sup> Also, the probability of being within a given distance of a vertical tree trunk with a vertical dipole antenna can be estimated from this parameter. The effects on antenna driving-point impedance as a function of distance from a vertical tree trunk have been measured and modelled by Vichit.<sup>34</sup> This parameter is important in computing mismatch loss for antennas operated in a forest.

## 8.0 MEASUREMENT TECHNIQUES AND LIMITATION

### 8.1 Earth Electrical Properties

The various techniques for measuring the electrical properties of ground have been reviewed by Lytle<sup>35</sup> at this workshop. Another comprehensive review of this topic was prepared by Maley<sup>36</sup> who participated in 1967 workshop<sup>37</sup> where these techniques also were discussed. The IEEE Wave Propagation Standards Committee has recently adopted a set of standardized techniques for ground constant measurement.<sup>38</sup> One must be careful to pick the appropriate technique for the measurement situation involved. It should be noted that there are difficulties in measuring conductivity at very high frequencies where  $\sigma \ll \omega \epsilon$ ,

and there are corresponding difficulties in measuring relative dielectric constant ( $\epsilon_r$ ) for cases where  $\sigma \gg \omega \epsilon_r \epsilon_0$ .

## 8.2 Vegetation Electrical Properties

The various techniques for measuring vegetation constants have been reviewed by Hagn.<sup>26</sup> The open-wire transmission line technique is useful for frequencies below approximately 100 MHz. For higher frequencies, the only known techniques for in situ measurements involve fitting propagation models or antenna pattern models. These techniques have decreasing utility above  $\approx 500$  MHz and probably have no validity for  $\epsilon_r$  above about 1 GHz. The Recve-Adams technique has potential utility at LF, MF and the lower part of the HF band.<sup>30</sup>

## 9.0 CONCLUSIONS AND RECOMMENDATIONS

The conclusions and recommendations are divided into two categories: those which can be implemented without additional research through the use of existing information, and those which require additional research and development.

### 9.1 Recommendations for Use of Existing Information

#### 9.1.1 Information Retrieval and Dissemination

It was concluded that much data currently exists in the R & D community but that this information is widely disbursed and is not generally known or available to DOD users. It is recommended that an information retrieval system tailored to the specific body of information covered in this workshop be established and maintained at the Defense Documentation Center. Such a system would include a user's guide containing the appropriate key words etc. and the capability for generating literature surveys.

#### 9.1.2 Texts, Handbooks and Instructor's Manuals

While this workshop has provided a start towards pulling together the information available on the design, operation and performance evaluation of radio systems in forested areas, it is still necessary to integrate this information into the documents described below:

- An engineer/physicist text on radio systems in forested areas that will put all the germane material in a single volume, analogous to the Rad Lab series prepared after World War II.
- A field user's handbook, which will be at a lower technical level than the text, and will describe for the man in the field the most desirable practices for typical operational situations. The format could be question-answer or comic book narrative (like some existing field maintenance guides).
- Texts for the Signal Corps schools and doctrine should be

reviewed for accuracy and currency and rewritten as required. The requirement for documents devoted solely to the topic of operations in forested areas should be reviewed.

- An instructor's manual should be written to provide a guide which parallels the classroom text(s) and at the same time provides the instructor with more depth in the subject. The manual should also provide references so the instructor can easily learn of other work to increase his knowledge as he finds necessary.

#### 9.1.3 Computer Model Users Guide

A computer model users guide should be generated. This guide should include models for antennas, propagation, noise and interference and radio systems performance. The type of information required includes: model name, definitive reference(s), general purpose, special features, status of development and validation, availability (source and format), input required, outputs generated, limitations (frequency, distance, antenna heights, etc.), input data availability (source and accuracy). The guide should also indicate how to run the models (if at all) when the input data are incomplete. An indication of preferred models should be made for commonly occurring operational and design situations, including running cost as a criteria.

#### 9.1.4 Model Comparison and Parametric Sensitivity Study

Existing models for the same purpose (e.g., calculation of basic transmission loss in forests) should be run with the same input data and the results compared. A standard set of problems, useful as diagnostics, should be generated to facilitate checking models after software modification or after a change of computer. A parametric sensitivity study should be performed for each model to identify the most significant parameters and to help indicate the accuracy required for the environmental input data.

#### 9.1.5 Relating Physical and Electrophysical Environments

The state of the art should be documented (beyond that possible in this workshop) regarding our current ability to infer the electrophysical properties of the forest environment needed to run analytical models from our knowledge of the physical environment as provided by foresters and biogeographers. This should be done for the cases where we can and cannot have direct access to the forest.

#### 9.1.6 Check of Other Sources of Forest Environmental Data

A check should be made of the intelligence community and other sources of classified information for both reports on techniques of categorization of the forest environment as well as for data on forests of interest. Also, NASA should be checked for methods of handling ERTS and similar data.

#### 9.1.7 Information Flow Between R & D Community and DOD User Community.

WG IV attendees concluded that this workshop helped considerably to facilitate information flow between DOD users of R & D information (e.g., Dr. Kitchen, who is tasked with calibrating the Canal Zone test range for radio purposes) and the R & D community who generated the needed technical information. DOD managers should continue to take the initiative in making sure that the results of work done under DOD R & D contracts reaches the DOD operational and test and evaluation personnel in a form they can use.

#### 9.2 Recommended Research and Development

##### 9.2.1 Refined Relationships Between Physical and Electrophysical Environments.

Additional research and development will be required to establish better relationships for estimating electrophysical parameters from information on the physical environment obtained from maps, overflights, satellite data etc. The relationships between data required for mobility studies in forests and communication studies in forests should be investigated. The utility of physical models should be explored.

##### 9.2.2 Validation of Existing Antenna, Radio Propagation and System Performance Models.

Existing models should be checked by making predictions followed by field measurements at U.S. test ranges and proving grounds. This procedure would help in the calibration of test ranges and proving grounds for future communications, radar and sensor equipment tests as well as provide data useful for assessing the confidence with which existing models can be used. Current models are not well verified!

##### 9.2.3 Measurement of Vegetation Electrophysical Parameters

Better methods for measuring vegetation electrical parameters below 100 MHz should be developed. Advanced open-wire transmission line probes should be tried and the wave impedance method of Reeve and Adams should be better developed and checked. The antenna pattern measurement method should be further developed using statistical techniques, especially for 100-1000 MHz. New techniques are needed for  $f > 1\text{GHz}$ .

##### 9.2.4 Biomass, Biodensity and Forest Effective Height

The relationship between biomass as measured by foresters, the effective height of the forest as required in the slab models, and biodensity as related to what open-wire transmission line probes measure should be further explored. The relationship between forest effective height and tree height as measured by foresters needs better definition.

#### 9.2.5 Ground Electrophysical Parameters

The use of surface ground electrical parameters which vary with frequency in antenna and propagation models should be further explored, and the results should be compared with those produced by models assuming frequency-independent parameters. Ground electrophysical parameters should be measured as a function of radio frequency over longer time periods (e.g., at least several times a day for one year at the same site) to determine both diurnal and seasonal variations of surface values.

#### 9.2.6 Climatological Investigations

The primary investigations in and above forests should define humidity, liquid water content, and temperature as a function of height and atmospheric pressure to facilitate studies of ducting, etc.

#### 9.2.7 Moisture Content of Vegetation

Ground-based techniques for measuring the moisture content of living vegetation should be further explored, with emphasis on microwave techniques. Also remote sensing techniques (overflight, satellite, etc.) involving the use of radiometers, scatterometers, and multispectral photography should receive additional attention. Attempts to relate moisture content to electrophysical properties should continue.

#### 9.2.8 Network Approach to Forest Propagation Analysis

The 2-port and 4-port network approach to analyzing propagation in forests should receive renewed attention. Modern network analyzers should be useful, especially at microwaves, to study the effects of polarization, meteorological effects (wet vs. dry, wind blowing or not) as a function of time for both shorter and longer time intervals. Such work could help identify important variables at the higher frequencies.

#### 9.2.9 Effective Antenna Height and Irreducible Error in Propagation Models.

A major source of uncertainty in radio propagation models is the specification of the effective antenna height in irregular terrain. This topic should receive further study, and the concept of an essentially irreducible error (i.e., irreducible standard deviation,  $\hat{\sigma}$ , of the difference between model prediction and measurement sample) should be explored. Such an irreducible  $\hat{\sigma}$ , if it exists for a given model and terrain category, would provide guidance regarding the accuracy of required environmental data for that model and terrain. It could also provide a method of estimating the improvements to be expected from proposed model refinements.

9.2.10 Relationship Between Military Scenarios and Radio System Performance Models

The relationship between selected military scenarios and radio system performance models should be reviewed and a methodology for specifying and obtaining environmental input data should be further developed. The methodology and model should be checked during field exercises, especially those conducted at test ranges.

9.2.11 Two-Point Correlations

Methods must be developed for measuring (or inferring) the 2-point correlation function of a forest, as required for models of propagation through random media.

9.2.12 Remote Sensing of Forests

Empirical relationships between the macroscopic electrical properties of forests and the outputs from remote sensors, such as synthetic aperture imaging radars, radiometers, etc. should be sought using a multi-frequency, multi-polarization approach.<sup>39</sup>

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## MAJOR FINDINGS, CONCLUSIONS AND RECOMMENDATIONS

C. W. Bergman, Working Group Chairman

1. The participants in the working groups of the workshop understood, it is believed, that the objectives, although highly commendable, could not be fully realized during their stay at Fort Huachuca, but that this was a necessary beginning.

2. Time did not allow a full investigation of how all present operational radio or radar systems could benefit by applying knowledge which already exists. Nor was there sufficient time to identify all areas of future research applicable to existing or planned radio systems. However, it seems clear that some generalized recommendations can be made which, if followed, will move us toward realization of the stated objectives.

(1). The texts used for the training of personnel in all service schools should be reviewed in order to determine if the material is compatible with the findings of the research efforts. These texts should be expanded to include R&D findings as noted herein, pertinent to their subject matter.

(2). Appropriate R&D results should be condensed into a single graduate level textbook on the subject of electromagnetic systems in forested or foliated environments.

(3). Present propagation models need to be better qualified by further comparison with measured data and then made available to the various users with full explanation of their capabilities and remaining constraints.

(4). Further effort (in addition to 3 above) is needed on the existing models, but this should be identified with and bounded by specific operational needs.

(5). In order to more effectively apply results of the research to operation problems there must be a further mutual exchange of information between the operational and the research people to better identify specific problems.

3. To more fully realize objectives of the workshop (and also move toward better application of SEACORE and related findings), further contact is essential among key personnel of the following military groupings:

(1). Research, development and engineering organizations.

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(2). Schools and training activities.

(3). Operating agencies.

A series of smaller scale, less formal meetings than this workshop are needed to address detailed needs, problems and trade-off aspects involved in problem-solving for the various interests noted in (1) thru (3) above. It is, therefore, suggested that a small group of those who have detailed knowledge and understanding of the research done under the SEACORE Program be made available to discuss the application of this research with the school and training activities and with the several operating commands. Once this is done, it will be possible to outline a development program for each agency towards realization of the details of their particular solution. Coordination between agencies could be greatly aided by the R&D group, thus ensuring a minimum of duplication among various interests.

3. In conclusion, it is agreed by all that a great deal of applicable information and experience was obtained in the SEACORE Program which can be and should be applied in order to improve existing and planned radio systems; further, that much of the money spent in doing the research will have been wasted without the incremental effort needed to do this.

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APPENDIX B: SUMMARY OF REPORTS AND ARTICLES FROM PROJECT SEACORE,  
SPONSORED BY THE ADVANCED RESEARCH PROJECTS AGENCY  
AND THE U. S. ARMY ELECTRONICS COMMAND

Prepared by: M. Acker, G. H. Hagn and R. A. Kulinyi

1. PREFACE

The paper by R. A. Kulinyi defines the scope and provides an overview of Project SEACORE (a part of ARPA's Project Agile). This appendix is a list of reports (and articles printed through July 1973) summarizing the results of Project SEACORE. Other reports and articles on forest propagation and related topics exist that were done as part of ARPA's Project Agile but not as part of SEACORE, and likewise documents exist that were part of ECOM's overall effort in this area but were not part of SEACORE. Most of these documents are referenced in the papers in this report, or in their references. Although the list of SEACORE reports is now complete, additional articles incorporating SEACORE results are in preparation.

The following list of reports is arranged by contract, and the articles are listed at the end.

2. Title: "Tropical Propagation Research"

Contractor: Atlantic Research Corporation  
(Jansky and Bailey Research and Engineering Dept)  
5390 Cherokee Avenue  
Alexandria, Virginia 22314

Contract: DA 36-039 SC-90889, ARPA Order 371

a. Semiannual Reports

- (1) Semiannual Report 1 - July - Dec 62 AD 609 284
- (2) Semiannual Report 2 - Jan - June 63 AD 609 285
- (3) Semiannual Report 3 - July - Dec 63 AD 609 286
- (4) Semiannual Report 4 - Jan - June 64 AD 451 045
- (5) Semiannual Report 5 - July - Dec 64 AD 460 634
- (6) Semiannual Report 6 - Jan - June 65 AD 474 377
- (7) Semiannual Report 7 - July - Dec 65 AD 486 499
- (8) Semiannual Report 8 - July - Dec 66 AD 662 267
- (9) Semiannual Report 9 - Jan - June 67 AD 486 499
- (10) Semiannual Report 10- July - Dec 67 AD 676 870
- (11) Semiannual Report 11- July - Dec 68, J. J. Hicks and  
R. G. Robertson AD 697 158
- (12) Semiannual Report 12- Jan - June 69, R. G. Robertson  
AD 708 902

b. Final Reports

- (1) Volume I - Oct 67 AD 660 318
- (2) Volume II - Nov 69, J. J. Hicks, A. F. Murphy,  
E. L. Patrick and L. G. Sturgill, AD 706 232
- (3) Volume III-Nov 70, R. G. Robertson, J. J. Hicks,  
C. B. Sykes and P. A. Anti, AD 714 300
- (4) Volume IV-Dec 72, J. J. Hicks, R. G. Robertson,  
C. B. Sykes, and P. A. Anti, AD 755 257

3. Title: "Research Engineering and Support for Tropical Communications"

Contractor: Stanford Research Institute  
333 Ravenswood Avenue  
Menlo Park, California 94025

Contracts: DA 36-039 AMC-00040 (E) ARPA Order 371; and  
DAAB07-70-C-0220 (The four reports prepared  
under this ECOM contract (STRs 39, 42, 45 and  
46) are so indicated.)

a. Semiannual Reports

- (1) Semiannual Report 1 - Sept 62 - Feb 63, W. R. Vincent  
AD 480 589
- (2) Semiannual Report 2 - Mar 63 - Aug 63 AD 480 590
- (3) Semiannual Report 3 - Mar 64 - Aug 64 AD 458 523
- (4) Semiannual Report 4 - Sept 64 - Mar 65, R. E. Leo,  
C. H. Hagn and W. R. Vincent AD 474 163
- (5) Semiannual Report 5 - Apr 65 - Sept 65, G. H. Hagn,  
H. W. Parker and E. L. Younker AD 486 466
- (6) Semiannual Report 6 - Oct 65 - Mar 66, G. H. Hagn,  
E. L. Younker, and H. W. Parker AD 653 608
- (7) Semiannual Report 7 - Apr 66 - Sept 66, E. L. Younker,  
G. H. Hagn, and H. W. Parker AD 653 615
- (8) Semiannual Report 8 - Oct 66 - Mar 67, E. L. Younker,  
G. H. Hagn, and H. W. Parker AD 675 459

b. Final Reports

- (1) Final Report Volume I - Sept 62 - Feb 64, (Sept 1964)  
AD 480 594
- (2) Final Report - Task I, "Counterinsurgency Communi-  
cations Requirements in Thailand (U)", Y. Lucci  
(Dec 1966) CONFIDENTIAL. AD 380 555
- (3) Final Report - Sept 62 - Feb 70, G. H. Hagn and  
G. E. Barker (Feb 1970) AD 889 169

c. Special Technical Reports (STR) and Research Memoranda (RM)

- (1) STR 1, "Communications Systems Implications of Thai  
Speech", K. Dimmick, (June 1965). AD 473 557
- (2) RM 2, "Voice Tests on Manpack Radios in a Tropical  
Environment", W. R. Vincent, (July 1963). AD 480 591
- (3) RM 3, "Field Tests on Manpack Radios in a Tropical  
Environment", W. R. Vincent, (July 1963). AD 472 860
- (4) RM 4, "Scale-Model Measurements on a Sloping-Wire  
Antenna", T. S. Cory, (June 1963).
- (5) RM 5, "Orientation of Linearly Polarized Hf Antennas  
for Short-Path Communications via the Ionosphere near  
the Geomagnetic Equator", (Aug 63, Revised June 1964),  
G. H. Hagn AD 418 497 and AD 480 592
- (6) RM 7, "Measured Impedances of Some Tactical Antennas  
near Ground", T. S. Cory and W. A. Ray, (Feb 64)  
AD 480 593
- (7) STR 8, "Field Tests of VHF Manpack Radios",  
N. K. Shrauger (Apr 65) AD 480 587
- (8) STR 9, "Absorption of Ionospherically Propagated HF  
Radio Waves under Conditions where the Quasi-Transverse  
(QT) Approximation is Valid", G. H. Hagn, (Sept 64)  
AD 480 588

- (9) STR 10, "Full-Scale Pattern Measurements of Simple HF Field Antennas", W. A. Ray, (May 66) AD 487 49
- (10) STR 11, "The Use of Ground Wave Transmission-Loss and Intelligibility-Test Data to Predict Effective Range and Performance of VHF Manpack Radios in Forests", G. H. Hagn, (Sept 66) AD 672 061
- (11) STR 12, "Survey of Literature Pertaining to the Equatorial Ionosphere and Tropical Communication", G. H. Hagn and K. A. Posey, (Feb 66) AD 486 800
- (12) STR 12 - Addendum, "Subject Index for Survey of Literature Pertaining to the Equatorial Ionosphere and Tropical Communication", C. H. Hagn, K. A. Posey, and H. W. Parker, (Oct 66) AD 805 545
- (13) STR 13, "Feasibility Study of the Use of Open-Wire Transmission Lines, Capacitors, and Cavities to Measure the Electrical Properties of Vegetation", H. W. Parker and G. H. Hagn, (Aug 66) AD 489 294
- (14) STR 14, "Faraday Rotation Measurements of Electron Content near the Magnetic Equator using the Transit IV - A Satellite", C. L. Rufenach, V. T. Nimi, and R. E. Leo, (Jan 66). AD 486 729
- (15) STR 15, "Comparison of C-2 Ionospheric Sounder Data with Frequency Predictions for Short-Range Communication with Manpack Transceivers in Thailand", C. L. Rufenach and G. H. Hagn, (Aug 66) AD 662 065
- (16) STR 16, "A Note on the Computed Radiation of Dipole Antenna in Dense Vegetation", J. Taylor, (Feb 66) AD 487 495
- (17) STR 17, "Literature Survey Pertaining to Electrically Small Antennas, Propagation Through Vegetation, and Related Topics", J. Taylor, K. A. Posey and G. H. Hagn (Jan 66) AD 629 155
- (18) STR 18, "Ionospheric Sounder Measurements of Relative Gains and Bandwidths of Selected Field-Expedient Antennas for Skywave Propagation at Near-Vertical Incidence", G. H. Hagn, J. E. van der Laan, D. J. Lyons, and E. M. Kreinberg, (Jan 66) AD 489 537
- (19) STR 19, "Preliminary Results of Full-Scale Pattern Measurements of Simple VHF Antennas in a Eucalyptus Grove", G. H. Hagn, G. E. Barker, H. W. Parker, J. D. Rice, and W. A. Ray, (Jan 66) AD 484 239
- (20) STR 20, "Human Factors in Thai Counter-insurgency Communications," A. D. Levandosky, (Jan 66) AD 825 327L
- (21) STR 21, "Controller's Data Display Mark II - Instruction Manual", S. E. Wahlstrom, (Jun 66) AD 486 799
- (22) STR 22, "Survey of Existing Communications Systems in Thailand (U)", CONFIDENTIAL, D. A. Price (May 66) AD 377 365

- (23) STR 23, "Communications in Low-Intensity Counter-insurgency: A Study of the Border Patrol Police in Thailand (U)," SECRET, J. A. McLeod and R. E. Morse, (May 66) AD 383 804L
- (24) STR 24, "Communications Traffic Requirements to Support Counterinsurgency Operations against Medium-Level Insurgency in Thailand (U)," CONFIDENTIAL A. Gualtieri, (May 66) AD 377 364
- (25) STR 25, "Full Scale Pattern Measurements of Simple Field Antennas in a US Conifer Forest," W. A. Ray, G. E. Barker, and S. S. Martensen, (Feb 67) AD 653 165
- (26) STR 26, "Initial VHF Propagation Results Using Kelelop Techniques and Low Antenna Heights", N. K. Shrauger and K. L. Taylor, (Dec 66) AD 653 609
- (27) STR 27, "Manual for ARN-3 Type Atmospheric Noise Measurements Equipment," R. L. Brown, (Nov 66), AD 653 780
- (28) STR 28, "Evaluation and Prediction of Maximum Usable Frequency (MUF) over Bangkok," C. L. Rufenach, (Jan 67) AD 655 566.
- (29) STR 29, "Electrical Ground Constants of Central, Eastern, and Northeastern Thailand," T. Kovattana, (Feb 67) AD 661 058
- (30) STR 30, "Three Techniques for Measurement of Ground Constants in the Presence of Vegetation," N. E. Goldstein, H. W. Parker and G. H. Hagn (Mar 67) AD 672 496
- (31) STR 31, "Orientation Measurements in Thailand with HF-Dipole Antennas for Tactical Communication," LCDR. P. Nacaskul, R.T.N., (Jun 67) AD 675 460
- (32) STR 32, "Ionospheric and Magnetic Observations at Bangkok, Thailand, During the Annular Solar Eclipse on 23 November 1965," J. E. van der Laan, (Dec 67) AD 672 068
- (33) STR 33, "Measurements of Equatorial Magnetic Dip Angle at Ionospheric Heights," V. T. Nimit (May 67) AD 662 064
- (34) STR 34, "Measurements of Electron Content and Latitudinal F-Layer Critical Frequency near the Magnetic Equator," V. T. Nimit (Feb 68) AD 647 461
- (35) STR 35, "Full-Scale Pattern Measurements of Simple HF Field Antennas in a Tropical Forest in Thailand," G. E. Barker and G. D. Koehrsen (Feb 68) AD 647 739
- (36) STR 36, "Selected Examples of VHF Signal Propagation Records in Tropical Terrains," N. K. Shrauger and E. M. Kreinberg (Nov 67) AD 672 070
- (37) STR 37, "Analysis of Median-and-High-Frequency Atmospheric Radio Noise in Thailand," R. Chindahporn and F. L. Younker (May 68) AD 681 878

- (38) STR 39, "Full-Scale Pattern Measurements of Simple VHF Antennas in Thailand Tropical Forest", G. E. Barker and W. A. Hall, (Dec 71) (This report was published under Contract DAAB07-70-C-0220) AD 738 177
- (39) STR 40, "Further Evaluation of Frequency Predictions for Short-Path Radio Communications in Thailand", V. T. Nimit, (Jan 68) AD 675 462
- (40) STR 41, "A Study of the Electromagnetic Properties of an Isolated Tree", V. Lorchirachoonkul, (Feb 68) AD 687 298
- (41) STR 42, "Open-Wire Transmission Line Techniques for Measuring the Macroscopic Electrical Properties of a Forest Region", J. Taylor, Ching Chun Han, Chung Lien Tien, and G. H. Hagn, (Jun 72) (This report was published under Contract DAAB07-70-C-0220) AD 755 551
- (42) STR 43, "Electric Constants Measured in Vegetation and in Earth At Five Sites in Thailand", H. W. Barker and W. Makarabhiromya, (Dec 67) AD 674 740
- (43) STR 44, "VHF Diffraction and Groundwave Propagation Tests Using Ionospheric Sounders", J. E. van der Laan, D. J. Lyons, D. J. Barnes, and G. H. Hagn, (Jun 68) AD 720 598
- (44) STR 45, "Measurement and Modeling of the Radiation Patterns of Simple HF Field Antennas over Level, Mountainous and Forested Terrains", G. E. Barker, J. Taylor and G. H. Hagn, (Dec 71) (This report was published under Contract DAAB07-70-C-0220) AD 737 724
- (45) STR 46, "VHF Propagation Results Using Low Antenna Heights in Tropical Forests", G. H. Hagn, N. K. Shrauger and R. A. Shepherd, (Mar 73) (This report was published under Contract DAAB07-70-C-0220) AD 768 205
- (46) STR 47, "HF Atmospheric Radio Noise on Horizontal Dipole Antennas in Thailand", G. H. Hagn, R. Chindahporn and J. M. Yarborough, (Jun 68) AD 681 879
- (47) STR 49, "The Counting of Lightning Flashes", E. T. Pierce, (Jun 68) AD 682 023

d. Ionospheric Data Reports

- (1) "Ionospheric Data: Bangkok, Thailand", September 63-March 67, V. T. Nimit:  
 AD 800 613, AD 800 614, AD 480 574, AD 800 615,  
 AD 800 616, AD 800 617, AD 800 618, AD 800 619,  
 AD 800 620, AD 480 575, AD 480 576, AD 480 577,  
 AD 480 587, AD 800 621, AD 800 622, AD 480 579,  
 AD 480 580, AD 480 581, AD 485 491, AD 480 582,  
 AD 800 623, AD 480 624, AD 480 583, and AD 800 625

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- (2) "Vertical-Incidence Ionospheric Data: Thailand",  
April 1966 - March 1967, B. E. Frank and G. H. Hagn,  
(Dec 67) AD 669 601

e. Geophysical Data Reports

- (1) "Faraday Rotation Data: Bangkok, Thailand",  
November 1964 - June 1967, V. T. Nimit, et al.,  
AD 436 677, AD 488 204, AD 807 773, and AD 819 257.  
(2) "Atmospheric Radio Noise Data, Bangkok, Thailand",  
March 1966 - February 1968, R. Chindahporn, et al.,  
AD 653 616, AD 652 685, AD 653 164, AD 662 771,  
AD 663 801, AD 663 802, AD 665 382.  
(3) "Geomagnetic Data, Bangkok, Thailand", January 1966 -  
December 1966, D. J. Barnes and J. Chapman:  
AD 659 407, AD 667 957, AD 665 377, and AD 667 958

4. Title: "Basic Laboratory Operation and Support"

Contractor: Stanford Research Institute  
333 Ravenswood Avenue  
Menlo Park, California 94025

Contract: DAAH01-70-C-0550; ARPA Order 1544

- a. Final Report, J. E. van der Laan and S. W. Lewinter,  
(Sept 73) AD 914 577L

5. Title: "Additional Communication Studies"

Contractor: Stanford Research Institute  
333 Ravenswood Avenue  
Menlo Park, California 94025

Contract: DA 28-043 AMC-02201(E)

- a. Report: "A Field Guide to Simple HF Dipoles", C. Barnes,  
J. A. Hudick and M. E. Mills, (Mar 67) AD 684 938  
b. Final Report: "Field Test of AN/GRA-93 ( ) HF Antenna Kit  
for Short-Path Skywave Communication in Thailand Forest  
Environment", G. H. Hagn, D. J. Barnes, J. W. Chapman,  
J. E. van der Laan, D. J. Lyons and J. P. Muro (Aug 67)  
AD 661 100

6. Title: "An Experimental Study of Radio Wave Propagation  
In Simulated Forests and other Dissipative  
Environments"

Contactor: Polytechnic Institute of Brooklyn  
Electrophysics Department  
Brooklyn, New York 11201

Contract: DAAB07-68-C-0222; ARPA Order 1101

a. Semiannual Reports

- (1) ECOM-0222-1, 14 February 1968 - 14 August 1968,  
T. Tamir (Sept 68) AD 680 30
- (2) ECOM-0222-1, 16 June 1968 - 15 December 1969,  
T. Tamir (Jan 70) AD 720 99

b. Final Reports

- (1) ECOM-0222-F, 14 February 1968 - 14 March 1969,  
T. Tamir (Apr 69) AD 697 79
- (2) ECOM-0222-F, 16 June 1969 - 15 June 1970,  
T. Tamir (Mar 71) AD 725 77

7. ECOM SEACORE Reports

- a. T. Tamir, "The Role of the Sky and Lateral Waves on  
Propagation in Forest Environments," (Mar 67) AD 651 639
- b. D. Dence (ECOM) and T. Tamir (Polytechnic Institute of  
Brooklyn), "Transmission Losses in a Forest for Antennas  
Close to the Ground", Research and Development Technical  
Report ECOM 2940, (Feb 68) AD 669 608
- c. T. Tamir, "On the Electromagnetic Field Radiated above  
the Tree Tops by an Antenna Located in a Forest",  
Research and Development Technical Report ECOM 3443  
(Jun 71) AD 733 278

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## 8. SEACORE Articles

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